DOCTOR OF PHILOSOPHY

Assessing the performance of combined sustainable drainage and ground source heat devices in heating a domestic building

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Award date:
2013

Awarding institution:
Coventry University

Assessing the performance of combined sustainable drainage and ground source heat devices in heating a domestic building

SUBMITTED

BY

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

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FACULTY OF BUSINESS, ENVIRONMENT AND SOCIETY

COVENTRY UNIVERSITY

FEBRUARY 2013

Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at Coventry University or any other institution.

Amal Faraj

Abstract

A field study of the feasibility and the performance of a sustainable drainage technique combined with a renewable energy device to provide heating in a domestic setting was carried out from March 2008 to November 2010 to acquire practical data about the system's operation.

Among all the sustainable drainage techniques, permeable pavement system (PPS) was selected to be applied in this project since this particular technique can be used for driveways and car-parking hard standings, but more specially they can be designed as a tanked system whereby an impermeable membrane is installed at the bottom of the tank in order to hold the rainwater collected as runoff from hard areas and roofs before releasing it in a controlled manner. The renewable energy device applied in this study is a ground source heat pump system (GSHP), which has been found in previous studies to provide a better performance when installed in wet conditions. Based on this, the PPS and the GSHP with horizontal ground heat exchanger (GHE) were integrated in a 350mm deep reservoir under 'real life' conditions. The combined system operated in heating mode in a family–sized, three bedrooms detached *EcoHouse* at the Building Research Establishment Innovation Park, Watford, UK. Monitoring the combined system included taking measurements of the temperature of the conditioned space, the ground around the PPS/GSHP system, and of the ambient air every 10 minutes.

Assessing the performance of the PPS/GSHP system involved investigating the effect of extracting heat via the GHE on the ground temperature, the impact of the PPS/GSHP on the thermal profile of the air above the surface of the reservoir, and computing the PPS/GSHP coefficient of performance (CoP).

The thesis includes information about the design of the PPS/GSHP system including the structure of the sub-base, types and size of the used aggregate and stone, the depth of the excavated reservoir amongst others, also the technical problems that materialized, largely due to the fact that the PPS/GSHP was installed and operating under real-life circumstances. Results obtained from the study provided evidence for the workability of the combined system in regards of stormwater management and of providing heat to the EcoHouse. However, monitoring the rainwater stored in the reservoir showed that, due to leakage, the top part of the buried coil was not covered with water. The monitoring also revealed that the rainwater surrounding parts of the coil was, in severe weather, frozen. Moreover, highly significant correlations ($p<0.01$) were calculated for the ambient air and the ground temperature relationships with the CoP. All of these factors resulted in a 1.8 coefficient of performance being obtained. This low figure was related to the shallow depth of the reservoir since it became clear that its ground temperature was greatly influenced by the ambient air temperature. The study also revealed that the evaporation process was prevented from occurring due to the Inbitex™ composite layer, as a result there was no significant effect on cooling the thermal profile of the air near the surface of the pavement. Furthermore, it was concluded that continuous heat extraction from the ground contributed to an underground temperature drop.

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Acknowledgements

I would like to thank the following people for their advice, ideas and guidance throughout this work. I would never have made it without their support.

Dr. Susanne Charlesworth – Director of Study
Thank you for the conception of the project, your academic guidance, critical judgment, encouragement, and support. For your patience and for understanding my feelings when I went through tough times. Without your advice, the quality and strength of this work could not have been attained.

Dr. Stephen Coupe – Supervisor
Thank you for giving me the opportunity and for the trust. Special thanks for all the driving from Coventry to BRE at Watford in order to carry out the field work, and for all the discussions, industrial and academic guidance and the supply of literature.

Dr. Les Duckers – Supervisor
Thanks cannot be extended enough to you for all the invaluable advice which helped my thesis to have a better value. Thanks for suggesting valuable papers, books, authors etc.

Coventry University
For giving me the opportunity to do a further study and more specially for supporting this project financially. Having a bursary that was allocated for this project for three years was a great enhancement to make the decision to study abroad, away from my home country.

Hanson Formpave Plc employees and managerial staff
Thanks for allowing me to use the Hanson EcoHouse as part of my research. Hanson-Formpave literature which was such a great help to understand the construction of the building and the PPS/GSHP, especially in my first year, and was very helpful during my writing up when I needed some information and images of the EcoHouse.

Building Research Establishment (BRE)
I would like to thank BRE staff for being so friendly and always giving me a welcome feeling whenever I was there to monitor the EcoHouse and to collect water samples. Special thanks go to Mr. Graham and his wife not only for the friendly atmosphere but also for reporting their observations regarding the thermal conditions of the inhabited space inside the EcoHouse, power failure, visitors' impact, etc.

Lab Technicians
Special acknowledgment for the assistance and explanation of how to use the ICP received from the technicians in the James Starley lab at Coventry University, especially Anne Nuttal and Neil Thompson.

Dr. Heitham Al-Hajieh
Who was a PhD colleague and became a close friend later during my PhD journey. Thanks for helping me with understanding statistical issues, data processing and in talking about various topics when I needed a break from studying.

Special thanks to my family in Libya: My mother, father, sisters and brother, my nieces and nephew, and 'Doody' my best friend who is considered as a family member, for having faith in me, for their care, attention and prayers.

My family-in-law in the UK who so much understood my studying circumstances, helping in any way that they could when I was working on family visits, for their care and for their interest in my research progress and for encouraging me to keep going !

Elwyn Lloyd – My husband
My research would have been considerably harder without my husband in my life.

Dedication

I dedicate this work to my Dad and Mam

Abbreviations

List of used abbreviations:

ASHP	Air Source Heat Pump
ASTM	American Society for Testing and Materials
BERR	Business, Enterprise and Regulatory Reform
BMP	Best Management Practices
BRE	Building Research Establishment
CGP	Concrete Grid Pavers
CIBSE	Chartered Institute of Building Services Engineers
CIRIA	Construction Industry Research and Information Association
CLG	Department for Communities and Local Government
CO_2	Carbon Dioxide
CoP	Coefficient of Performance
CSH	Code of Sustainable Homes
DEFRA	Department of Environment, Food and Rural Affairs
DESA	Department of Economic and Social Affairs
EA	Environment Agency
EER	Energy Efficiency Ratio
FITs	Feed-In Tariffs scheme

GHE	Ground Heat Exchanger
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pumps
HGV	Heavy Goods Vehicles
ICP-AES	Ion coupled plasma atomic emission spectroscopy - a method for the determination of metals that offers multi-element determinations
IPCC	Intergovernmental Panel on Climate Change
PA	Porous Asphalt
PC	Porous Concrete
PP	Permeable Pavement
PPS	Permeable Pavement Systems
PPS/GSHP	Permeable Pavement System integrated with Ground Source Heat Pump
PTRG	Plastic Turf Reinforcement Grid
RE	Renewable Energy
RHI	Renewable Heat Incentive
SEPA	Scottish Environmental Protection Agency
StD	Standard Deviation
SuDS	Sustainable Urban Drainage Systems
US EPA	The US Environmental Protection Agency

Units

EJ: Exajoule is a derived unit of energy. EJ is equal to 10^{18} joules

Tj: Terajoule is a derived unit of energy. Tj is equal to 10^{12} joules

GWh: Gigawatt hours. Gigawatt is equal to 10^{9} watt

mg: milligram is equal to 10^{-6} Kg

µg: microgram is equal to 10^{-6} g

Chapter 1 : Introduction

1.1 SuDS: rationale

Since more areas of the world are becoming urbanized, with more migration from villages and farms to cities and towns, the extension of the built environment and paved surfaces is increasing inexorably (Pandey *et al*., 2003). The UK Department of Economic and Social Affairs (DESA, 2005) reported that the global proportion of the population that lives in urban areas rose from 13% (220 million) in 1900, to 29% (732 million) in 1950, to 49% (3.2 billion) in 2005. The same report projected that the figure is likely to rise further to 60% (4.9 billion) by 2030. With this urban population growth, the acuteness of a number of environmental problems has increased. The major issues associated with increasing urbanization are climate change, scarcity of fresh water, management of rainwater runoff and flooding, and fresh water contamination. The following sections discuss how some of these problems may be mitigated through applying Sustainable Drainage Systems (SuDS).

1.1.1 Climate Change

Climate change reflects the strong global warming trend that scientists have observed over the past century or so, some concluding that the start of the upward trend in temperatures can be linked to the Industrial Revolution (Schreiner, 2004; Martinez, 2005; Forster *et al*., 2007; Le Treut *et al*., 2007; Barca, 2011). The aspect of most concern are the changes associated with the significant global temperature rises causing a host of other climatic impacts such as changes in the means and variance of rainfall, producing higher localized temperatures, drier summers and wetter winters, bringing on aridity, drought, flooding and affecting agriculture/food production and water availability (Arnell, 2004).

Also, rates of evaporation can vary a great deal, depending on temperature and relative humidity, which impacts on the amount of water available to replenish groundwater supplies. In fact, some changes seem to be already quite advanced; temperatures in some regions have been increasing at twice the global average and recent years have witnessed a dramatic reduction in summer sea ice cover and ice thickness in the Arctic Circle, and extreme weather conditions appear to be increasing in both magnitude and frequency (IPCC, 2007; Barber *et al*., 2008; Min *et al*., 2008; Kaufman *et al*., 2009).

Recent evidence and predictions indicate that the changes are accelerating and will lead to wide-ranging shifts in climate variables. In the UK, the Department of Environment, Food and Rural Affairs (DEFRA, 2010) is expecting an increase of 16% in average winter rainfall in the North West side of the UK by the 2080s, with increases in the amount of rain on the wettest days. Climate change should be considered in the context of all of the stresses and influences on water resources, so that it is counted as a major contributor in flooding problems and water quality impairment. The flooding in the UK in the summer of 2007 showed the devastating impact that can result from sudden heavy downpours; this storm event caused the flooding of 55,000 properties and left 350,000 people without mains water (DEFRA, 2010), with total economic costs ranged between £2.5 - £3.8 million

(EA, 2010). When the potential increase in rainfall due to climate change is considered, along with the lack of permeable surfaces for the rain to soak through in urbanized areas, then a significant additional load to the average annual runoff is inevitable.

Another, exacerbating impact due to climate change is human migration, which is the typical response to local aridity as people naturally seek to move to safer and more productive areas. However, Pandey *et al*. (2003) suggested that rather than migrating to different areas, people may resort to modifying the conditions in their environments by adopting new strategies to conserve water such as rainwater harvesting. SuDS introduce different techniques that help manage rainwater runoff (this will be explained in detail in Chapter Two); thus, they may mitigate this problem occurring as a result of urbanization and industrialized environments. The other major environmental problem that has been associated with urbanization is urban runoff, and the need to apply SuDS to help in reducing some of the contributing causes of this will be explained in the following section.

1.1.2 Urban Runoff

Natural landscapes, such as forests and grasslands, allow rainwater and snowmelt to filter slowly into the ground. Since more societies and nations have become industrialized and witnessed very large-scale and rapid urban population growth, the area of land covered by impervious surfaces, such as roads, pavements, rooftops and also car parks and driveways, has increased hugely. The shortage of natural landscape and permeable surfaces means a reduction in the chances of rainwater percolating naturally through the soil. It instead leads to an increase in the volume and rate of precipitation runoff, a decrease in the effects of a valuable filtering mechanism for runoff through soil and vegetation, a lowering of the water table, more frequent and severe flooding and potential damage to public and private property. In urban areas, the overriding aim is to remove large quantities of surface water as quickly as possible by directing cumulative runoff straight into sewer pipes, the capacity of which is clearly limited. The US Environmental Protection Agency (US EPA, 2003b) reported that impervious cover in a typical city leads to five times the runoff of typical woodland of the same surface area as shown in Figure 1-1.

Figure 1-1: Relationship between impervious cover and surface runoff
(Source: US EPA, 2003)

Stormwater entering the conventional piping system does not usually receive any treatment before it is discharged to its final destination, which may be streams, lakes or any other surface waters, and thus can cause impaired water quality downstream. Moreover, the capacity of the existing pipe network in the sewer infrastructure is increasingly insufficient. When rain falls intensively, large quantities of high velocity water collected from non-porous surfaces in a short period surge through the network with a higher volume than the sewer can handle, resulting in unmanageable runoff and flooding.

Alternative or supplementary measures alongside the conventional methods of runoff control are vital. Such an alternative is presented through SuDS techniques, allowing for stormwater management practices that can ease the pressure on ageing sewer systems. Aside from the flooding problem, another issue associated with runoff from urbanization areas is that of water quality. The link between runoff and water quality was highlighted by Taebi and Droste (2004) who pointed out that urban runoff is increasingly recognized as a significant cause of water quality impairment (see also: Pitt *et al*., 1999; Reeves *et al*., 2004).

1.1.3 Water Quality

Many studies have proved that urban development has an adverse effect on both the quantity and quality of surface water runoff. In built-up areas, the impacts of traffic emissions, industrial pollution, and of much human activity in general are high and elevated levels of atmospheric pollutants are released. The most common urban stormwater pollutants include sediment, heavy metals, oils and hydrocarbons, and oxygen-demanding substances leached from roads and parking lots (Brown & Peake, 2006). This is in addition to fertilizers and pesticides from lawns, and zinc from galvanized guttering and roofs. Grit and road salt used to melt snow and ice on roadways and pavements can also be washed out with stormwater adding contamination to streams and groundwater (USGS, 2010). This collection of high pollutant loads can accumulate as dry deposition and is washed off the ground or out of the atmosphere during rainfall events (Helmreich & Horn, 2009). The contaminated rainwater is then conveyed to the receiving watercourse (such as rivers, lakes, and sea) (Barbosa *et al.*, 2012) without receiving any treatment (Charlesworth *et al.*, 2012); this is recognized as a major environmental problem (Qin *et al.*, 2011).

As well as having a negative effect on the water quality of runoff due to urbanization, increased population concentrated in cities and towns puts higher strain on water resources. It is vital, nonetheless, that water quality is maintained to ensure that there is safe drinking water and food production. Construction activity disturbs and exposes the subsurface of large areas in cities and towns, leading to soil erosion during episodes of heavy rain and its subsequent transportation to streams and lakes (Collins *et al.*, 2008) and resulting in: a) excessive suspended sediment that harms aquatic life and leads to an increase in water-treatment costs, and b) sedimentation that clogs drainage ditches, stream channels, water intakes and reservoirs, and which damages or even destroys aquatic habitats.

Runoff as a result of urbanization is a major factor in the deterioration of water quality through the discharge of rainwater contaminated with oil, heavy metals, and so on, to a watercourse. Moreover, when runoff collects following a summer storm, the temperature of the water is increased due to the absorption of heat emitted from roads and other surfaces; sudden increases in stream temperature can be caused, which in turn can produce thermal shock in many aquatic habitats (US EPA, 2003a). Contaminated runoff contains bacteria, protozoa and viruses that can be transmitted to humans, as well as to animals and plants in the food chain, and this may even be life-threatening to the very young, very old or those with weak or impaired immune systems. The channelling of polluted water from impermeable surfaces into watercourses is a threat to water quality and amenity. An effective control of urban rainwater runoff and flooding that involves reducing the velocity and flow of stormwater as well as reducing pollutant discharges is vital. SuDS are a solution to reduce the costs and potential hazards in the future as they may be used to decrease the quantity and increase the quality of urban runoff accumulated as a result of trends in urbanization.

One of the other major environmental concerns is CO_2 emission from the use of fossil fuels. Measuring the CO_2 emission resulting from using the Ground Source Heat Pump (GSHP) in this particular project was not part of the research; nonetheless, an overview of this aspect and the role of renewable energy in reducing greenhouse gases (GHG) are presented in the following section in order to show the necessity of using GSHP for heating and cooling purposes in reducing the release of CO_2.

1.2 Renewable Energy: rationale

The world's energy generation depends predominantly on burning fossil fuels (coal, oil, and gas). However, they are non-renewable resources which, on the one hand, will dwindle eventually as they are finite, and on the other hand, and more immediately, the process of burning fossil fuel releases emissions of GHG, such as carbon dioxide (CO_2), into the atmosphere, resulting in serious environmental pollution problems. The Intergovernmental Panel on Climate Change (IPCC, 2001) reported that the atmospheric concentration of CO_2 has increased by 31% since 1750, around the time of the start of the Industrial Revolution. Carbon dioxide makes up some 72% of the GHG, which could be contributing to global climate change (IPCC, 1992). In 2001, the IPCC also reported that about three-quarters of anthropogenic emissions of CO_2 to the atmosphere during the past 20 years are due to fossil fuel burning, with an average annual increase of 1.8% (IPCC, 2001; IEA, 2004). Domestic energy consumption accounts for 47% of UK CO_2 emissions, and of this 75% is due to energy consumed to provide heating and cooling (Parliamentary Office of Science and Technology, UK, 2010).

At the Kyoto summit of 1997, it was agreed that the European Union would reduce CO_2 emissions by 8% by 2010. The UK agreed to an individual target of a 12.5% reduction in CO_2 emissions, but its government believed it could cut emissions by up to 20% below 1990 levels by 2010 (DETR, 2000). Nonetheless, a recent Press Release by Cambridge Econometrics (2010) revealed "the previous government's domestic goal of a 20% reduction in carbon emissions by 2010 seems likely to be missed only by a very narrow margin", and the 2010 provisional official data indicated a 16.5% reduction by 2010. It was also reported that in June 2011 the Coalition government accepted legally binding, ambitious carbon budget targets up to 2027 (Cambridge Econometrics, 2012). In the context of reducing CO_2 emissions, more efficient use of energy and increased use of renewable energy (RE) appear to be the most desirable and effective solutions (Hepbasli, 2008). Tackling domestic CO_2 emissions can be achieved by applying an efficient RE system that can provide heating and cooling to domestic (and commercial) buildings without burning fossil fuel, thus leading to a reduction in emissions of GHG and contributing to the reduction of the effects of climate change (HM Government, 2009; Hwang *et al.*, 2009). The challenge is particularly acute for the EU-set target that 15% of UK total energy demand is to be met by RE by 2020 (DECC, 2012), in order to contribute to the 20% target for the EU as a whole.

There are different approaches of RE, for example solar, biomass and geothermal energy, which can be applied to meet space heating demands. However, since sunlight arriving on Earth is the most fundamental RE source in nature, a ground source heat pump (GSHP) system, also known as geothermal heat pump (GHP), was used in this research. The GSHP extracts stored heat from the earth or ground water by means of a ground heat exchanger (GHE), consisting of straight or coiled pipes buried under the ground (either horizontally or vertically) and coupled to a heating and cooling system in the inhabited space.

Over the past two decades, many experimental and numerical investigations into GSHP mainly focused on vertical GHE configurations, for example Mei and Fisher (1983), Petit and Meyer (1998), Spilker (1998), Chiasson & Spitler (2001), Pahud and Matthey (2001), Hepbasli (2002), Hepbasli *et al*. (2003) and, to a lesser extent, horizontal GHE, for example Laurent *et al*. (1987), Tarnawski (1989), Svec and Palmer (1989), Petit and Meyer (1997). In recent years, Fan *et al*. (2007) used a vertical configuration of an integrated GSHP system with a soil cold storage to study theoretically the effect of underground water flow on a ground heat exchanger's performance for a whole year. The results indicated that, both in heating and cooling periods, underground water flow enhances heat transfer. Bakirci (2010) has recently evaluated the performance of a dual 53m deep vertical GSHP system in a cold climate region of Turkey. The experimental results showed a coefficient of performance (CoP) of 2.6 across the seasons. Inallı and Esen (2004) studied the performance of a horizontal GSHP experimentally from November to April in heating season of 2002 – 2003, also in Turkey. The heat exchanger in their study was buried at depths of 1m and 2m. The CoPs of the system resulting from applying the heating mode in the winter season were found to be 2.66 and 2.81, respectively. Another experimental study is presented by Trillat-Berdal *et al*. (2006). They studied a solar-assisted GSHP system used in a 180m^2 residence with a vertical configuration of the GHE. The solar heat was used for water heating and the excess solar energy (when the preset water temperature is reached) was injected into the ground. Solar energy injected into the ground represented 34% of the heat extracted, and the heat pump's CoP in heating mode was at an average value of 3.75. The thermal performance of different types of underground heat exchangers was reported by Li *et al*. (2006). The thermal performance and ground temperature variation for a concrete piled foundation heat exchanger in a vertical configuration were investigated by Gao *et al*. (2008) and Wood *et al.* (2010).

In a study by Omer (2008) the benefits of GSHP systems were summarized. It was concluded that GSHPs were suitable for heating and cooling buildings and could play a significant role in reducing CO_2 emissions. The study emphasized that although the cost of GSHP systems is more than that of conventional systems, they have very low maintenance costs, and they are reliable and environmentally-friendly systems. The GSHP advantages of high energy efficiency and substantial reduction of CO_2 emissions have been reported in a number of publications, for example Jenkins *et al*. (2009), Blum *et al*. (2010), and Sivasakthivel *et al*. (2012). Badescu (2007) investigated the economic feasibility of different active space heating systems, namely GSHP with oil, natural gas, and electricity. The results showed that GSHP has the advantage of a much lower investment cost. Esen *et al*. (2006) also performed an economic analysis for a GSHP system. The horizontal GSHP was set up for space heating and was monitored under real operational conditions for 7 months (November 2002 - May 2003). The researchers concluded that GSHP offers economic advantages over conventional heating methods (electric resistance, fuel oil, liquid petrol gas, coal, oil and natural gas).

The results of two different studies were published by Yu *et al*. (2010 and 2011) which were based on the heating and cooling of an archives building in

Shanghai, China. The GHE consisted of 280 boreholes to a depth of 80m. They concluded that heat injected to the ground during the cooling mode reduced the heat absorbed from the ground during the heat extraction (heating mode) by 20% (2010). They also concluded that after one year of the GSHP operating in the cooling mode, the soil temperature increased by only 0.5°C (2011). Furthermore, it was found that when compared with an air source heat pump (ASHP) system and water cooled unit with a boiler system, the operating cost of the GSHP was reduced by 55.8% and 48.4%, respectively (Yu *et al*., 2011). In an earlier study, De Swardt and Meyer (2001) compared experimentally, and with simulations, the performance of a reversible GSHP system with that of ASHP systems. The results showed that GSHP systems in heating mode yielded significant heating capacity (24%) and efficiency improvements (20%) over ASHPs.

In a recent study by Karabacak *et al*. (2011), a vertical GHE buried in soil at a 110m depth was part of a GSHP installed in Denizli, Turkey. The relationships of the performance coefficients of the GSHP with meteorological data including solar radiation, wind speed, relative humidity and external temperature collected in this experiment were reported. In an experimental comparison made by Urchueguía *et al*. (2008) between a GSHP system and a conventional air to water heat pump system it was found that, under the same climatic conditions and for a whole climatic season, the GSHP could save energy by 43 ± 17% when working in heating mode and 37 ± 18% when the system was working in cooling code. In Greece, Michopoulos *et al*. (2007) used a GSHP in a building with an area of 1350m^2. The ground temperatures were measured and the CoP values and energy consumption were calculated. They concluded that there was an increasing trend of the seasonal CoP during the three years operation in heating mode and a decreasing trend for the cooling mode. These results were accredited to the fact that heat was injected during the cooling mode into an already high temperature ground, which had a stronger influence on the heating mode rather than on the cooling operation.

All these studies and others described in the literature help in informing researchers, in shaping government policy, driving new markets, and above all they result in benefits for people generally in times of increasing focus on efficiency and sustainability.

1.3 Justification of the research proposal

The potential for meeting the target that 12% of the UK's needs for heat energy should come from renewables by 2020 could be jeopardized unless a realistic strategy is adopted and implemented as widely as possible. The UK domestic sector currently relies heavily on conventional systems for space heating; approximately 80% of the UK's domestic water and space heating demands are met using gas boilers (Utley and Shorrock, 2008). Therefore, using a renewable source for heating demands for domestic settings, such as GSHP, could play a significant role in supplying domestic heat without adding to the UK GHG emissions. It is, however, necessary to study a long-term application of the GSHP in real conditions to determine under what circumstances a GSHP may cause thermal degradation in the ground and whether its efficiency can be maintained for several years. Singh *et al*. (2010)

pointed out that there is a lack in the UK of specific data and research into this topic. A lack of data on long-term GSHP applications in cold climates makes the decision to install one more difficult. Due to the increased focus on sustainability, the GSHP in this study was integrated with a permeable pavement system (PPS) which is one of the SuDS techniques. While the GSHP is aimed at utilizing the renewable geothermal energy, the PPS is to contribute in mitigating flooding events and in improving water quality. There is now a need for an integrated approach to overcome environmental problems as much as possible. The sustainable hybrid GSHP system (GSHP system that is combined with some type of supplemental heat rejecter are commonly referred to as hybrid GSHP system) in this study has been constantly monitored over three years. The two systems were combined since it has been verified in the past decade, for example Leong *et al. (*1998), Rawlings and Sykulski (1999), Permchart and Tanatvanit (2009), Gonzalez *et al.* (2012), that a better performance of the GSHP is achieved in saturated and part-saturated environments rather than being in a dry surrounding. This is because the higher the water content of the surrounding environment is, the higher the value of thermal conductivity is (Leong *et al.,* 1998). Such a system could make use of stored rainwater as the first heat source/sink and a heat transfer fluid is circulated within a buried underground pipe to transport heat stored in the subsurface to the above-ground heating system of a building for heating purposes.

GSHPs are energy-efficient, environmentally clean, low maintenance, and cost-effective heating and cooling systems (Omer, 2008). Instead of revealing outcomes (from theoretical/laboratory studies) along statistical grounds, an

EcoHouse envelope located at Watford, UK has been used as a field trial to determine the thermal performance of a PPS/GSHP for a domestic application in real conditions.

The system is appealing because the scale of opportunity is vast: a single system has the potential to capture, detain and treat runoff and to simultaneously take energy from the water or from the soil, to provide cooling, heating and hot water for buildings nearby (Tota-Maharaj *et al.*, 2009), thus eliminating the need for separate boiler and air-conditioning systems, and helping individuals to reduce their fuel bills and contribute towards meeting the national carbon reduction target. The dual use of rainwater as a supplementary water supply and as a heat transfer medium would enhance the economics of GSHPs. This research aims to provide evidence of the feasibility of the combined system, which should support those in the industry wanting to sell the best products and services. It is also expected that this novel system will contribute towards the high level of sustainability requirement standards of the Code for Sustainable Homes (CSH) in the UK.

Novelty and timeliness of the project

This project has the following novel aspects:

I. Installing a GSHP space conditioning system designed by Hanson Formpave Ltd. to make use of rainwater stored in a PPS as a supplementary heat source is a new approach.

II. The use of a GSHP combined with a PPS to meet the heating requirements of a domestic setting under real-life conditions without resort to an additional heating system during the cold season.

III. Installing the PPS/GSHP system in a shallow reservoir (350mm) in order to obtain heat from the ground. Such a shallow reservoir has not been reported in the literature; therefore, installing the GHE at such depth is original.

IV. Collecting temperature readings for a GSHP setting at a 10-minute interval for nearly three years for the conditioned space, and around 20 months for the ground temperature readings.

1.3.1 Thesis rationale, aims and objectives

1. Determining the feasibility of a RE device combined with a sustainable drainage technique at a domestic setting for heating purposes.
2. To determine the performance of a GSHP designed to make use of harvested rainwater.

The main objectives can be classified as follows:

1a. To provide the configuration and construction of the combined system installed in real-life conditions on a full-size detached two-storey EcoHouse in order to study the feasibility of integrating the two systems.

1b. Identify and solve design and construction problems which might arise.

1c. Continuous monitoring of the temperature of the habitable space inside the EcoHouse building, the ground thermal distribution of the PPS/GSHP reservoir, and of the ambient air temperature; and whether comfortable conditions for habitation inside the EcoHouse are provided year round.

1d. To study, in the local climate and in an uncontrolled environment, the validity of installing the integrated system in a shallow reservoir.

2a. To determine the coefficient of performance (CoP) of a GSHP used in an integrated system. Discussing whether there are relationships between the CoP of the applied system with the air temperature and ground temperature.

2b. To investigate the potential influence of continuous heat extraction from the ground on the ground thermal condition, under realistic conditions, and on the performance of the system.

2c. To investigate whether the PPS/GSHP would have an effect on thermal conditions of the air near the PPS/GSHP pavement surface.

1.3.2 Thesis Outlines

Each of the following chapters describes a unique contribution towards a better understanding of PPS/GSHP systems used in a residential application. The related literature review is included in each chapter.

Chapter Two presents the concept of SuDS and their role in managing rainwater runoff. A general view of developing SuDS, their design, and the different types is presented. More specific information regarding the SuDS techniques which were used in the current study, including their design characteristics, usage, and types is given. Also, the reason for choosing PPS to be applied at this project is demonstrated. The UK legislation orientated towards ensuring better water quality and a reduction in rainwater runoff is highlighted as well.

Chapter Three provides a broad picture of PPS showing their construction specifications and possible applications, the structural design of the systems, their ability to allow rainwater to infiltrate through gaps between the pavement blocks, and to improve the water quality.

Chapter Four explains different types of RE systems that can be applied for domestic air conditioning. The reason for selecting GSHP as the RE system to be applied in this research is also discussed. Moreover, the UK laws and policies that have been recently introduced in order to accelerate the uptake of RE and the government support to individuals willing to adopt an RE system are presented.

Chapter Five of the thesis includes a thorough literature review of previously published studies covering concerns pertaining to the GSHP system. The concept of GSHP, the effect of applying the GHE in different conditions (moisture-laden soil, snow cover, etc.), a description of GSHP components, the different configurations of the GHE (vertical, horizontal and slinky) are all explained. The efficiency of GSHPs, their ability in reducing energy consumption, and contribution towards reducing GHG emissions are discussed. Towards the end of the chapter, the economic benefits and economic concerns are outlined.

Chapter Six describes the site on which the field trial took place; the level 4 CSH EcoHouse constructed at Watford, UK, the PPS and the PPS/GSHP systems are illustrated. Experience gained while installing the PPS/GSHP is also presented. The tools for monitoring features at the site and the collected data are demonstrated.

Data collected from site are analysed in Chapter Seven. The data of the EcoHouse inhabited space is presented as 'all years', yearly, and monthly temperature analyses. The temperature fluctuations according to seasonality in ground and in air temperature are also presented.

In Chapter Eight the CoP of the PPS/GSHP during heating periods is calculated. The correlations between the ambient air, the ground temperature and the CoP are computed. Also in the chapter, the effect of extracting heat from the ground, and the impact of the PPS/GSHP on air temperature are analysed.

Chapter Nine is the discussion chapter, and conclusions and recommendations for future work are presented in Chapter Ten.

Chapter 2 : Sustainable Drainage Systems

Introduction:

This chapter outlines the role of SuDS in managing rainwater runoff and in improving water quality. The development of SuDS, their design and role in improving water quality and quantity, types of SuDS, and the reasons for selecting permeable pavement system (PPS) to be the SuDS technique applied for domestic settings are also explained. The introduction of new legislation, regulations, policies and guidance that are aimed at promoting the possibility of domestic buildings actually contributing towards a better environment is discussed at the end of this chapter.

2.1 SuDS development and design

Traditionally, runoff from impervious surfaces is captured through gutters, guttering, and other drainage channels or conduits and the collected rainwater is directed straight into piped sewer systems, usually underground. In recent years, emphasis has shifted toward local on-site treatment and management of stormwater at source rather than this being passed downstream. SuDS create space for water by legitimizing its transgression into urban spaces and providing pollution source control for less hazardous forms of waste water (Jones and Macdonald, 2007).

Initially, the term '*SUDS*' was the acronym for the UK approach of sustainable urban drainage systems. However, the need to improve the drainage of surface water in both urban *and* rural contexts has led to the emphasis on 'Sustainable drainage systems' instead; thus the "urban" part of SUDS is now usually dropped to reduce confusion (but the acronym is maintained as SuDS, only with a lower-case 'u'). In Australia, SuDS are known as water-sensitive urban design, and as low-impact development and Best Management Practices (BMPs) in North America. In the latter region they have been recognised since 1972, following the introduction of the Clean Water Act (US EPA, 1999).

Harvested rainfall is counted as a renewable source of relatively clean water which can be collected from roads, parking lots and rooftops. This can increase or supplement the water supply for various domestic and landscape uses, for example watering gardens. Åstebøl *et al.* (2004) stated that the central element of sustainable stormwater management is the utilization of stormwater as a resource. However, water collected from contaminated areas often requires treatment to achieve water supply of sufficiently good quality for secondary uses such as irrigation. Contaminants, such as zinc, cadmium, and copper have the potential to endanger soil and groundwater when they are not sufficiently biodegraded and/or removed during infiltration (Dierkes *et al.,* 1999, 2002b, and 2005). Runoff contaminants in urban-residential and industry-dominated environments have been reported on by several researchers (Gromaire-Mertz *et al.*, 1999; Lee and Bang, 2000; Davis *et al.*, 2001; Lee *et al.*, 2002; McPherson *et al.*, 2005; Rule *et al.*, 2006). SuDS can be applied as a practical technique in order to utilize rainfall runoff and improve the quality of the surface water as it passes through the SuDS features. They are solutions that can also help to reduce the peak flow (Pratt, 1995 and 2004), disciplining surface water runoff and controlling it in a way which is amenable to humans (Jefferies *et al.*, 1999; Jones and Macdonald, 2007), insomuch that they allow for both the quantity and quality of the water to be managed. The philosophy of SuDS is to replicate, as closely as possible, the natural drainage from a site before the urban development altered it, which is encapsulated in the SuDS triangle (Figure 2-1) in which there is an equal balance between water quantity, water quality, and biodiversity/amenity (Charlesworth, 2010).

Figure 2-1: The SuDS triangle
(CIRIA, 2000a)

SuDS are processes that can mitigate many of the adverse effects on the environment of stormwater runoff. They achieve this through:

- Controlling the flow – volume and intensity, thus reducing the risk of downstream flooding;

- Reducing the additional runoff volumes and runoff frequencies that tend to be increased as a result of urbanization, and which can exacerbate flood risk and damage receiving water quality;
- Maintaining natural groundwater recharge;
- Reducing diffuse pollutant concentrations from surface water runoff, thus protecting the quality of the receiving water body by acting as a buffer and preventing direct discharge of high concentrations of contaminants into the receiving water body;
- Reducing the volume of surface water runoff discharging to combined sewer systems, thus reducing discharges of polluted water to watercourses via combined sewer overflow spills;
- Contributing to enhanced amenity including improvement in wildlife habitats and in the aesthetic value of a developed area.

  (US EPA, 1999; EA, 2002)

SuDS thus have four major benefits from a *drainage* point of view: reducing overall load on conventional drainage systems; holding back peak flows to prevent overloading; and intercepting urban runoff and removing pollutants before they enter watercourses (rivers, lakes, and ocean). They can be designed to provide an aesthetic landscape and habitat for wildlife in urban watercourses and encourage natural groundwater recharge (CIRIA, 2005; Jones and Macdonald, 2007).

SuDS was defined by Charlesworth *et al.* (2003) as a catch-all term for a number of different systems, which slow and sometimes retain runoff to attenuate surface drainage. SuDS can combine a series of different types of surface water management solutions (CIRIA, 2007), so rather than the rapid runoff from impermeable surfaces, SuDS instead completely overturn this principle by discharging runoff to one or more of the SuDS drainage techniques to be treated, such as a series of soakaways, grassed areas and swales (site control), ponds or wetlands (regional control) and permeable pavements (source control); it is the latter that is the focus of the present study. The catchment areas are therefore divided into smaller sub-catchments so the runoff passes successively at different stages of the discharge through different drainage techniques depending on land use and land characteristics; this process (see Figure 2-2) is known as a SuDS treatment train (CIRIA, 2000a).

Figure 2-2: SuDS treatment train
(Source: CIRIA, 2000a)

Some of the SuDS techniques focus on water quantity control, while others focus on improving water quality, however most perform both functions.

Water quantity control: there are several processes that can be used to manage and control the runoff and provide stormwater control, flood risk management, water conservation and/or ground water recharge. This can be achieved by:

- Infiltration: i.e. water soaking into the ground.
- Detention/attenuation: slowing down the surface flows before their transfer downstream.
- Conveyance: this is the transfer of surface runoff from one place to another.
- Water harvesting: this is the direct capture and use of runoff on site.

Water quality control: different processes will predominate for each SuDS technique for pollutant removal, which can be achieved by:

- Sedimentation: most pollution in runoff is attached to sediment particles and therefore removal of sediment by reducing flow velocities results in a significant reduction in pollutant loads.
- Infiltration and filtration: this may occur through trapping within the soil or aggregate matrix, on plants or on geotextile layers within the construction.
- Adsorption: this complex process occurs when pollutants attach or bind to the surface of soil or aggregate particles so a combination of surface reactions occurs.
- Biodegradation: this type of treatment happens when microbial communities may be established within the ground, using the oxygen

within the free-draining materials and the nutrients supplied with the inflows to degrade organic pollutants such as oils and grease.

- Volatilization: volatilization comprises the transfer of a compound from solution in water to the soil atmosphere, and then to the general atmosphere. In SuDS schemes volatilization is primarily concerned with organic compounds in petroleum products and pesticides.
- Precipitation: precipitation involves chemical reactions between pollutants and the soil or aggregate that transform dissolved constituents to form a suspension of particles of insoluble precipitates.
- Uptake by plants: is an important removal mechanism for nutrients and metals.
- Nitrification: ammonia and ammonium ions can be oxidized by bacteria in the ground to form nitrate, which is a highly soluble form of nitrogen.
- Photolysis: the breakdown of organic pollutants by exposure to ultra-violet light.

(Wilson *et al.*, 2004)

2.2 Types of SuDS

There are different types of SuDS techniques, but all depend on the basic idea of channeling and/or collecting stormwater runoff. They can be broken down into two main categories: hard SuDS, such as pervious hardstanding; and soft SuDS, such as ponds and wetland areas and vegetation-based systems. The SuDS Manual (CIRIA, 2007) distinguishes SuDS techniques as follows:

Source control and prevention techniques

- Green roofs
- Pervious hardstanding
- Rainwater harvesting
- Infiltration trenches
- Infiltration basins

Permeable Conveyance Systems

- Filter (French) Basins
- Swales

Passive Treatment Systems

- Filter strips
- Detention Basins
- Retention Ponds
- Sedimentation ponds
- Wetlands

As a detailed description of all SuDS techniques is not relevant to this current study, only three of the above techniques, namely rainwater harvesting, swale and pervious hardstanding, are explained as they are those that have been applied at the site monitored in the research project. Thus, they will feature prominently in this report.

Rainwater Harvesting (Water Butts for Runoff Capture and Re-use)

Harvesting of rainwater is simply the collection for domestic or commercial use of water that would otherwise escape into the drainage system. The purpose of rainwater harvesting is to re-use water and reduce rates of surface runoff. Some rainwater harvesting techniques are very familiar, such as the use of rainwater butts in gardens to collect and store the runoff from a roof via a drainpipe (see Plate 2-1). The water butt fills when it rains and the water is used for watering plants during dry periods.

Water butts include storage tanks, rain barrels and other similar receptacles that are used to capture rainwater and stormwater from the roofs of buildings. There has been a recent increase in the use of the collected water for a range of non-potable uses, particularly for flushing toilets (CIRIA, 2007). This will lessen reliance on mains water along with reducing runoff discharge.

Plate 2-1: A water butt at the BRE site

Swales

Swales (see Plate 2-2) are vegetation-based systems that are a type of SuDS commonly constructed along highways and which have been widely used as a runoff quantity, quality and amenity control. Revitt *et al.* (2004) revealed that the use of organic elements such as grassed swales and, in particular, reed beds can be extremely efficient at removing diffuse source pollution washed off from urban surfaces. Swales provide conveyance for runoff since the vegetation reduces peak velocity while infiltration reduces highway discharge. They have the potential for becoming wildlife habitats and to improve the aesthetic appearance of the highway environment. Also, they can be an alternative to the need for expensive roadside construction methods such as kerbs, gullies and thus reduce the costs of related maintenance.

Plate 2-2: An image and a diagram of a swale
(Source: CIRIA, 2012 a&b)

Swales have been used as an effective SuDS technique for stormwater disposal in many cities, for example in the City of Portland, Oregon, USA (Rogers and Faha, 2007). When this city was faced with the challenge of designing improvements for the 51-acre development of the 'Auto Warehousing Corporation' storage facility at the Portland port and docks area, the design team considered all options to manage the large volume of stormwater that could be generated as a result of surfacing the site. The preferred alternative constructed in the summer of 2006 was a porous pavement, which is a type of pervious hardstanding system (explained in further details in the next section), with vegetated swales to allow for the infiltration of 100% of the stormwater onsite.

The design characteristics of swales vary depending on the length and longitudinal slope. Most studies show that long swales with gradual slopes are more effective for removing pollutants because of the increased time available for settling and movement of the rainwater slowly through the grass for infiltration (Deletic, 2005; CIRIA, 2007). For a good hydraulic performance and low retention time, swales should have a minimum length of 30m, side slopes should be no greater than 1 in 4, and the base should be flat with a width between 0.5 and 2m (CIRIA, 2007). The pollutant removal efficiency of swales is achieved by mechanical filtering through vegetation, adsorption onto vegetation and microbiological breakdown of organic matter in the upper layers of the soil. To enhance their pollutant removal capacity, some regular maintenance is required, for example keeping the grass in the swale at a length of 150mm, and they should be designed to be dry between storm events (EA, 2000). Evidence of swales' efficiency in pollutant removal was concluded in a number of studies, such as Yu *et al.* (2001). They investigated the performance of two grass swales, one was a 274.5 m long with slope of 3% highway swale in Virginia, USA, which was monitored during natural storms, while synthetic runoff with prescribed pollutant concentrations was used in a swale in Taiwan (30m long with slope of 1%). Average pollutant removal efficiencies varied from 30 to 97% for total suspended solids, 29 to 99% for total phosphorus, and 14 to 24% for total nitrogen. In Brisbane, Australia, a controlled field test was undertaken to test the removal of total suspended solids, total phosphorus and total nitrogen on a grass swale (Deletic & Fletcher, 2006). The percentage of removal for the three parameters was 69, 46, and 56%, respectively.

Pervious hardstanding systems

The following section provides a broad picture of pervious hardstanding systems, as they constitute the main SuDS technique used in this research.

Pervious hardstanding systems can be grouped into two categories according to the method of infiltration; water can either infiltrate through the entire surface of the material, which then is called porous hardstanding, or between the gaps left between blocks of impermeable surfacing material, which is then called permeable hardstanding (CIRIA, 2007).

Pervious hardstandings are established as a solution to one of the principal shortcomings of soft SuDS infrastructure and they are set to become the norm for hard surfaces in all types of development. They can also be applied for small area space, whereas usually a large amount of space is required in order to install SuDS (e.g. swale). With pervious hardstanding, spaces are created for pedestrians and light vehicular traffic while allowing runoff from impermeable surfaces to pass through the paving surface and then infiltrate into the ground. This water can then make its way far more slowly through the soil to the nearest watercourse (CIRIA, 2000b; EA, 2003). Therefore, the choice was made to make use of this particular technique mainly because it can be employed in constructing driveways and/or hard surface front gardens that can be used for parking purposes outside a domestic building (Plate 2-3). A major factor contributing to flooding problems is the paved front gardens of domestic buildings (Wright, 2010).

Plate 2-3: permeable hardstanding employed for parking purposes
(Source: Interpave, 2012)

These small paved areas provide convenient off-road parking for homeowners but on the other hand they have added a dramatically high percentage to the existing impermeable surfaces, as seen in the following reports documenting 'urban creep' in some UK cities. Between 1971 and 2004 the development of impermeable surfaces in a suburban area of Leeds increased by 13%; the residential paved front gardens contributed to the development with almost 10% (Perry and Nawaz, 2008). Newcastle City Council carried out a survey focusing on urban creep in the Ouseburn area and concluded that it was highly dependent on the overall characteristics of the area, with the percentage of properties with a paved front garden ranging from 0 to 66% (Newcastle City Council, 2008). It has also been reported by the Greater London Authority that it is estimated that around two thirds of London's front gardens are already, at least partially, paved over (London Assembly, 2005). Although domestic front gardens are considered small, the large number of them can significantly impact on the flooding risk. For this reason, pervious hardstanding was the technique selected to be applied at the average-sized home at the centre of this research, since the domestic sector was the area of concern in the study.

Reducing runoff quantity collected from paved front gardens is not the only benefit of using pervious hardstanding in a domestic setting; the runoff can also be used for lowering the surrounding air temperature of the dwelling itself, and on a larger scale, the wider urban area. Rainwater that has infiltrated through the pervious hardstanding and is kept under the surface evaporates back through the pavement, resulting in the cooling down of the surface by the release of heat through water vaporization (Nakayama and Fujita, 2010). In contrast with concrete, asphalt, and similar materials that retain heat more effectively, pervious hardstanding causes heat from the sun to be reflected back into the atmosphere. This action can be one of the ways of addressing the heat excess caused by replacing natural vegetation with concrete, asphalt and so on, creating what is known as the 'urban heat island', and which is responsible for the higher temperatures measured in densely populated urban areas (Asaeda *et al.*, 1996; Dupont *et al*., 2006; Smith and Levermore, 2008). Traditional paved surfaces, such as impermeable asphalt and concrete, do not allow water to infiltrate but convert almost all rainfall from car parking lots or buildings into runoff directed to drain points (see Figure 2-3). However, replacing existing drainage pipes with larger ones to cope with increased rates and volumes of runoff may not be economical. Pervious hardstanding, with its ability to allow infiltration and storage of water, is one solution to these problems. It can be used as an effective measure for reducing flooding risk, and can play a significant role in groundwater recharge as well as in reducing hydraulic stress in sewer systems (Dierkes *et al.*, 2005).

Figure 2-3: A schematic diagram of pervious vs imperameable driveways (Source: CLG, 2009)

If even a relatively small amount of rainwater in a storm event can be allowed to infiltrate at a natural rate into groundwater, or can be kept in a sealed constructed tank rather than be allowed to flow as runoff, then a significant difference per dwelling or industrial premises can be made for local drainage. When good drainage practice is applied widely, the potential for a fundamental improvement in flood risk is clear. Figure 2-4 shows a classification of pervious hardstanding:

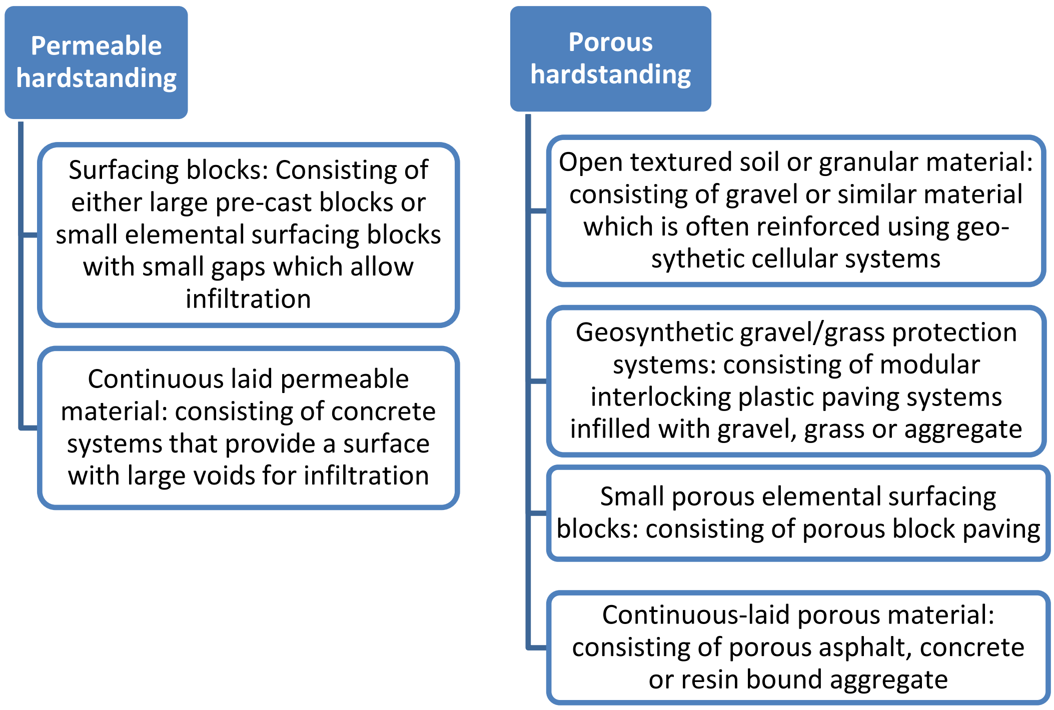

Figure 2-4: A classification of pervious hardstanding
(Adapted from Pratt *et al.*, 2002)

Several different types of porous and permeable hardstanding exist. The main differences between the pavement types are in the total pore space, spatial arrangement of the underlying pervious layers, and structural strength. The most common types of pervious hardstanding include porous concrete (PC), porous asphalt (PA), plastic turf reinforcement grid (PTRG), concrete grid pavers (CGP), and permeable pavement (PPS). Figure 2-5 depicts several of these pavement types together with sites names. The types of pavement are further discussed below.

Figure 2-5: Types of pervious hardstanding
(Source: Paversearch, 2010)

(a) Porous Concrete (Oregon Zoo sidewalk, Portland, Oregon, USA (Tennis *et al*., 2004)); (b) Porous Asphalt (A parking lot at the Pairie Ridge Sports Complex in Ankeny, Iowa, USA (LTAP, 2007)); (c) Plastic reinforcement grid pavers with earth and grass fill (A pathway at a golf course in Lancashire, UK (Rainbow Professional Ltd, 2013); (d) Concrete grid pavers with topsoil and grass fill (Carrabba's Restaurant installed an overflow parking, 14 stalls, Wilmington, NC, USA (Bean *et al*., 2004); (e) Permeable pavement (Used for footpaths, car parking, cycle racks and other paved areas at Hazeley School, Milton Keynes, UK (Interpave, 2008))

Porous concrete, also referred to as "no-fines concrete" is a strong, durable concrete material. This material is a mixture of Portland cement, fly ash, washed gravel, water, and, in some cases, fibre. Minimal or no fine aggregate is included in the mixture. The water to cementitious materials (w/cm) ratio is typically 0.35-0.45 (NRMCA, 2004). Unlike traditional installations of concrete, porous concrete usually contains a void content of 15-25%, depending on materials and intended application. Void content means that water can infiltrate directly through the pavement surface to the subsurface. Percolation rates of 100 to 750 litres per minute per square metre are common. These pavements are typically 10-20cm (4-8in) thick and may contain a gravel base course for additional storage or infiltration. Due to the high void content, pervious concrete is also lightweight, 1600 to 1900 kg/m^3 (100 to 120 lb/ft^3). Compressive strength can range from 2.8 to 28 MPa (400 to 4000 psi) (NRMCA, 2004), whereas a conventional concrete exhibits a compressive strength of up to 80 MPa.

Porous asphalt consists of fine and coarse aggregate bound by a bituminous-based binder and allows water to pass freely through to the underlying structure. It is used in commercial schemes, new housing developments, retail parks and car parks. As with porous concrete, fine particles are omitted to allow for a larger void space ranging from 15% to 20%. These voids enable rainwater to move from the pavement surface into the aggregate beneath it, where it can be stored until it eventually seeps into the natural soil beneath the aggregate. The thickness of the asphalt depends on the traffic load, but usually ranges from 7.5 to 18 cm (3-7 in). An underlying base course increases storage and adds strength (Ferguson, 2005).

Plastic reinforcement grid pavers, also called geocells, are strong, highly durable plastic interlocking cellular grids which retain the aesthetic appeal of grassed or graveled areas and are ideal for driveways and for gravel or grass car parks. They allow for infiltration through large gaps filled with gravel or topsoil planted with turf grass. A sand bedding layer and gravel base course are often added to increase infiltration and storage. The empty grids are typically 90-98% open space, so void space is dependent on the filling media (Ferguson, 2005).

Concrete grid pavers (CGP) can provide solid erosion control and good drainage at the same time. The American Society for Testing and Materials (ASTM), Standard Specification for Concrete Grid Paving Units (2001b) describes properties and specifications for CGP. Concrete grid pavers are typically 9 cm (3.5 in) thick with a maximum 60 x 60 cm (24 x 24 in) dimension. They allow rainwater to percolate through openings which range from 20 to 50% of the CGP and can be filled up with topsoil and grass, sand, or aggregate in the void space. The minimum average compressive strength of CGP should average 35 MPa (5,000 psi) with no individual one less than 31 MPa (4,500 psi). A typical installation consists of grid pavers with fill media, 25 to 38 mm (1 -1.5 in.) of bedding sand, gravel base course, and a compacted soil sub-grade (ICPI, 2004).

Permeable pavement, also known as permeable interlocking concrete pavement (PICP). A permeable pavement system of this type is what has been installed around the domestic building monitored in this research, and it will be referred to as PPS throughout this report. PPS is explained in details in the next chapter.

2.3 The UK government's approach towards SuDS

The European Union has responded to an increase in the perceived severity of flooding by introducing the Flood Directive 2007/60/EC for the assessment and management of flood risks. After the implementation of this Directive, the strategic risk assessment (SRA) of urban pluvial flooding has become a legislative requirement in many countries. Legislation regarding flooding and water in the UK is somewhat different to the legislation in other parts of the world, mainly because the UK has been relatively slow to adopt SuDS, and it could be said that SuDS practices are still in their infancy in this country.

In the UK, the Flood and Water Management Act (2010) (HMSO, 2010) places responsibilities on the EA for managing the risk of flooding in accordance with principles of sustainability, which involves recommending the application of SuDS for surface water drainage and flood control (EA, 2002; SEPA, 2005). In order to ensure that good water quality is maintained in all aquatic systems, a key piece of legislation has been set, namely the Water Framework Directive (WFD). However, considering the amount of pollution carried in discharged rainwater after washing off the roads, and the significant amount of metals from galvanized surfaces or roof sealant materials, there would be a high possibility of failure to address the tight WFD legislation, which demands that only extremely low levels of metals be allowed to infiltrate into the groundwater, or discharged to rivers, to prevent deterioration in water quality of catchments. Implementing SuDS in public spaces and at private residences can help to achieve the goal of the WFD as they can be used as runoff control systems with the ability to trap and treat pollutants.

The EA prepared an Interim Code of Practice for SuDS to help local authorities and developers implement these systems (EA, 2004). It describes the preparation and planning route, as well as current legislation and industry requirements for SuDS. The popularity of SuDS has resulted in the CIRIA Design Manual for England and Wales (CIRIA, 2000a), Sustainable Urban Drainage systems - design manual for Scotland and Northern Ireland (CIRIA, 2000b) and The SuDS Manual (CIRIA, 2007), which has replaced the previous manuals. These guides make reference to the current legislative framework and the responsibilities of regulatory authorities with regard to sustainable urban drainage. The other UK government authority that is responsible for policy and regulations on the environment is DEFRA, which has recently launched a SuDS standards consultation in the draft 'National Standards for Sustainable Drainage system' that has been developed to meet the requirements of the Flood and Water Management Act 2010, which effectively makes SuDS mandatory. The importance of source control, water management near the surface, a cost-effective operation throughout design life and integration of public space with SuDS are all aspects which are emphasized in the draft, and all are aspects in which concrete block permeable paving makes an invaluable contribution, indicating the common use of this SuDS technique.

SuDS help deliver EU Water Framework Directive objectives for improving water quality. The SuDS technique of concern in the current study is PPS, as mentioned above. This type of SuDS is suitable for domestic settings as it can provide a controlled source of clean water as a sustainable amenity for landscaping, ecology and water harvesting, and they can also be convenient to be used, for example, as a parking stand in front gardens. However, as of 1st October 2008 the legislation in England and Wales regarding permitted development rights for domestic front gardens has been changed. Planning permission now has to be obtained by householders intending to impermeably pave front gardens exceeding 5m^2 in order to make a hardstanding. Traditional impermeable driveways are considered as contributing to flooding and the pollution of water catchments, in contrast with the adoption of PPS, which will meet the legislative demand to help *reduce* flooding. Constructing driveways, paved front gardens and parking areas with permeable surfaces, such as concrete permeable paving blocks or gravel, will allow rainwater to soak into the ground and no planning permission is required in such cases (CLG, 2008). At present this legislation affects only new, replaced and extended installations at the front of a property adjacent to a road.

Additionally, the process of implementing environmental policy and standards in new buildings has reached the point that nowadays they are an integral part of the construction plan from the outset. In December 2006, the government published the Code for Sustainable Homes (CSH) to be the basis of future sustainable building standards in the UK housing sector (CLG, 2006). The CSH is a national standard for the sustainable design and construction of new homes and aims to contribute to the protection of the environment by providing guidance towards achieving the 'step-change' required to improve the overall environmental performance of new housing. The CSH is an environmental assessment method that measures the sustainability of a new home against categories of sustainable design, rating the sustainability performance of the whole home as a complete package and certifying the performance of new homes. CHS categories, credits available for each category, and the weighting of each category as a percentage are presented further in Chapter Six, Table 6-1.

Also, the government has set out planning rules such as Planning Policy Statement 25 (PPS25), which lays out policy on development and flooding risk by giving guidance to be followed at all stages in the planning process to avoid inappropriate building development in areas with high flooding risk, or to direct developments away from areas of highest risk (PPS25, 2006). This planning policy require local planning authorities (LPAs) to make the most of opportunities to reduce flood risk and to prepare surface water management plans (SWMPs) to help reduce the impacts of flooding through newly developed areas.

Both CIRIA (2000b) and EA (2003) agree that PPS should be applied for roadways, parking amongst others to enable rainwater to infiltrate through the paving surface. Taking all these facts into consideration it has become essential to find practical solutions to satisfy government authorities, as well as improving the quality and eco-efficiency of pavements at private residences. This could be achieved by adopting PPS at domestic settings. For example, Pratt *et al.* (1999) believe that the future of the UK's water environment is in householders' hands. They concluded that "ordinary people" are the key agent as they are the water consumers. The argument of Pratt *et al.* (1999) was that if a householder used stormwater runoff as a resource for reuse, thus modifying demand for water services, and also assisted with the implementation of new techniques to limit the discharge of low quality water to rivers and streams, this would help the householders themselves to achieve a clean supply of water combined with efficient protection from and disposal of 'waste' water at an economically viable cost, which would mitigate negative impact on the environment.

Summary

Implementing an effective technique, such as SuDS, to control rainwater runoff and flooding is essential. There are clear benefits associated with the use of SuDS techniques in order to reduce the volume of runoff and to improve the quality of the water.

In this chapter, the SuDS approach and its different types were introduced. There are a number of SuDS techniques that can be implemented for runoff management, however choosing the most appropriate technique depends on the specific site conditions. Among the SuDS techniques PPS has been identified as the most suitable method to be applied for front gardens and driveways at domestic settings. PPS was, therefore, the SuDS technique selected for the current study since domestic buildings are the focus of the research.

Homeowners thinking about adding a new drive, patio or other paved area at their property, including extensions, or replacing worn out paving with something more attractive, will need permission and will now need to comply with extra planning regulations. Adopting PPS around a domestic building would have a significant impact on rainwater runoff quantity and quality, and would also comply with government legislation that is aimed at promoting the possibility of domestic buildings actually contributing towards a better environment. The next chapter gives more extensive details regarding PPS.

Chapter 3 : Permeable Pavement

Introduction:

In the previous chapter, an overview about SuDS is given. This next chapter describes the SuDS technique used in this research, namely PPS. The structural design of the PPS, its efficiency in infiltration, and the effect of PPS on improving the water quality are all explained and evidence from the literature is presented.

For this research, this particular type of pavement was selected to be applied around a domestic settings over other permeable hardstanding types mainly because of its flexibility to be tailored to the “tanked system”, which would be employed to retain the harvested rainwater for re-use purposes (demonstrated in section 3.1); its high rate of infiltration as demonstrated in section 3.2; and also its higher efficiency in improving water quality (shown in section 3.3). Moreover, at the household level, Abdulla & Al-Shareef (2009) pointed out that the low cost, accessibility and easy maintenance of a rainwater harvesting system make it an attractive option. PPS pavers are available in many different shapes and sizes suitable for walkways, patios, public sidewalks, town squares and common areas (see Figure 3-1). The gravel in the joints provides 100% surface permeability and the base filters stormwater, thus, enabling recharge of the water table in addition to filtering and the reduction of pollutants. PPS can be used for parking areas, pedestrian paths, lightly trafficked driveways, sports grounds, bicycle and equestrian trails, pedestrian access and walkways. The following section illustrates the PPS structural design.

Figure 3-1: Different shapes and sizes of permeable pavement system (Source: Pavingexpert, 2010)

3.1 Permeable pavement structural design

This system generally consists of a surface layer, bedding layer course (pea gravel, small stone and sand), geotextile, sub-base and a possible extra geotextile bottom layer for added buffering of water (Figure 3-2). The surface layer is concrete blocks with vertical channels making the gaps in between each paver ranging between 8-20% of the surface area. The gaps are filled with 2-

4mm pea gravel and will allow water to seep down through an "open-graded" base. The essential function of the pavement surface is to support vehicular loads without undue deformation and to allow stormwater infiltration through to the pavement's sub-base. The ASTM C936 specifications (2001a) state that the pavers be at least 60mm (2.36 in) thick with a compressive strength of 55 MPa (8,000 psi) or greater depending on the purpose of use. The blocks lie on a 38 to 76mm (1.5-3 in) depth of 2-6mm of clean bedding crushed stone (ICPI, 2004).

Figure 3-2: Cross section of the Permeable Pavement structure
(Source: pavingexpert, 2010)

The next layer is the geotextile membrane which is a sheet of pervious polymeric compressed fibre with a size of 0.5 to 0.05 mm (0.02-0.002 inch) pores. This membrane should be laid on top of the sub-base overlapping joints by 300mm, which can be achieved by welding. Geotextile prevents the migration of fines from the sub-grade into the sub-base layer (Ferguson, 2005);

it is responsible for the majority of pollutant retention, it physically intercepts organic matter present in urban runoff, and it also functions as an appropriate substrate on which oil-degrading micro-organisms can grow and decontaminate retained hydrocarbons and herbicides (Coupe *et al.*, 2003; Coupe, 2004). Underneath the geotextile is the compacted sub-base, which can contain clean crushed stone, gravel or concrete having spaces in between to store water. The sub-base has a structural role in distributing the pavement's load to the underlying layers of gravel and soil, but also acts as a water storage layer and is sometimes referred to as the water saturation zone or reservoir course. The depth of the sub-base can be varied to suit the specific site conditions. However, it could be in two layers; 100mm depth top layer of 5-20mm stone size and a bottom layer with 250mm depth and 10-63mm stone size. The system storage capacity depends on the depth of the sub-base, the size of the aggregate and the ratio of voids. Apart from the sub-base materials mentioned above, limestone, blast furnace slag, pea gravel or granite can be used (Pratt *et al*., 1989). Additionally, for higher water storage capacity a 'geocellular box' can be installed as an alternative to the conventional granular aggregate sub-bases (Terram, 2012). Geocellular boxes are made of latticed plastic crate-like structures that are connected together to form a rigid structural raft, with some void ratios of up to 95% (e.g. these were installed in a permeable pavement at Hazeley School, Miton Keynes (Interpave, 2008)). The bottom layer is the sub-grade, which is normally made up of compacted local soil. The system is generally used in areas with high amounts of light traffic, such as shopping centre car parks (Pratt *et al.*, 2002; Mallick and El-Korchi, 2009). Permeable surfaces can carry occasional heavy goods vehicles (HGVs) traffic (< 5 commercial vehicles per day), however, for frequent HGV traffic, a PPS should be designed with certain specifications depending on site-specific factors such as the strength of the soil. Surfacing with permeable materials may not be the best option in many cases (CLG, 2009), even though the capabilities of these systems allow for such uses as parking space provision for HGVs.

Along with the benefits achieved by using SuDS through collecting, storing, treating, redistributing and/or recycling water, PPS has the advantage of enabling the utilization of harvested stormwater as a resource when it is constructed with an impermeable membrane placed under the sub-base layer (soil or aggregate), on which the paving blocks sit (Åstebøl *et al.*, 2004; Scholz and Grabowiecki, 2007). In other words, the PPS design can be adapted to fulfil the specific requirements of the site. Scholz and Grabowiecki (2007) argued that, regardless of water conservation concerns, where there is any concern about the possible migration of pollutants into groundwater PPS should be constructed with an impermeable membrane.

Typically, PPS can be used to control and manage runoff either as a soakaway, known as an infiltration system; or as a storage tank, and thus called a tanked or attenuation system. As presented in Figure 3-3, the infiltration system is underlain with a pervious geotextile and is suitable for use where it is proposed to allow the water to infiltrate directly into a suitable sub-grade. In a tanked system, the underlying pervious geotextile is replaced with an impervious membrane in order to attenuate storm water before releasing it in a controlled manner, harvesting the water for re-use, or where it is prudent to prevent infiltration in areas of problematic or contaminated sub-grades. If designed and implemented correctly, PPS can allow a large proportion of stormwater to infiltrate, thus reducing peak runoff volumes and flows (Andersen *et al.*, 1999; Sansalone and Teng, 2005; Sansalone *et al.*, 2008). Consequently, PPS can be considered as an effective tool for meeting those environmental or stormwater goals (Scholz and Grabowiecki, 2007).

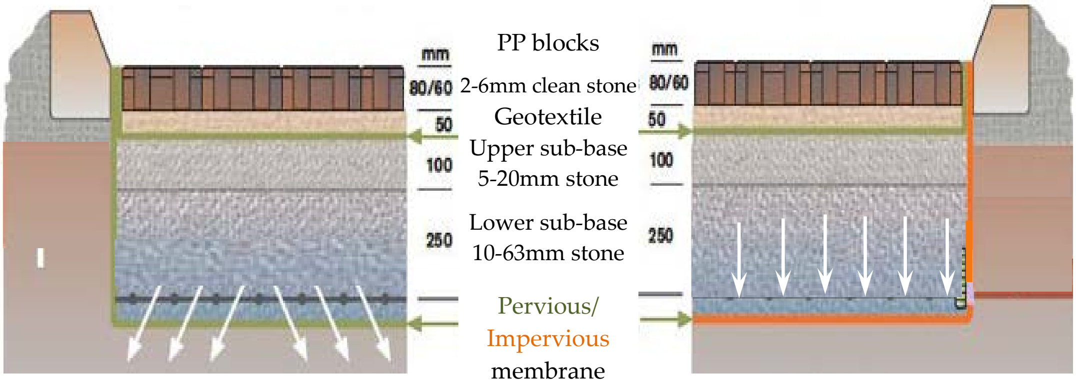

Figure 3-3: Typical design of PPS system.
The design of a filtration system is on the left and a tanked system on the right

(Source: Adapted from Hanson, 2010: 7)

3.2 Runoff infiltration through PPS

With urban runoff being one of the major causes of water pollution, stormwater management is becoming a high priority in many parts of the world. PPS is a type of pavement that promotes a high rate of surface infiltration, even in areas where the underlying soil is not ideal for complete infiltration. The installation of underlying drains in the PPS subsurface can yield reductions in outflow volume and peak flow rate, and delay the time to peak flow (Pratt *et al.*, 1989). Brattebo & Booth (2003) examined the long-term effectiveness of a pervious hardstanding parking area at Renton, Washington. The parking lot was constructed with five different types of pavement: standard asphalt, PPS filled with gravel, CGP filled with soil and planted with grass, PTRG with grass and PTRG filled with gravel (types of pavement are shown in Figure 2-5). Six years after installation, all the permeable sections had endured structurally. During 18 months of monitoring, 15 observable storms were recorded, during which virtually all rainfall infiltrated through each permeable section. On five occasions, small quantities of surface runoff were observed from the grass and plastic grid pavers, the largest volume of which amounted to 3% of the total precipitation.

The efficiency of PPS in attenuating peak discharges has also been confirmed in a number of other studies (Pratt *et al.*, 1999; Bean *et al.*, 2007b). Hunt *et al.* (2002) compared the hydrologic responses of various pavement sections including impervious asphalt, pervious concrete and two types of permeable interlocking concrete pavement. When compared to asphalt, all pervious pavement sections showed dramatically reduced surface runoff volumes, with the pervious concrete and interlocking concrete pavement blocks found to provide runoff coefficients of 0.2 to 0.5.

PPS basically are designed to mimic the function of soil by allowing the runoff after even an intense rainfall event to permeate in between the paving blocks into the ground below; consequently, it will reduce the hydraulic stress on traditional drainage. However, the accumulation and deposition of sediments and fine particles from the stormwater causes clogging of the surface void spaces (Balades *et al.*, 1995; Pratt, 1995). Fine particle deposition is typically a result of passing cars, wear of the pavement surface, or of transport via wind and runoff from nearby disturbed soils. Also, a greater likelihood of clogging may occur during construction, with mud and debris from building materials tending to be washed onto the site, clogging the pores. Trucks and tractors at the site compact the remnants resulting from the construction material and building activity, it is then ultimately transported down into the structure, reinforcing clogging problems on the surface (Siriwardene *et al.*, 2007). Vacuuming, sweeping and low-pressure washing are solutions for clogging problems; they should be used to clear out voids and extend the paver's functional life (James and Gerritts, 2003; Bean *et al.*, 2007a). In the worst case scenario, removing the top layer of the void space material should improve infiltration capabilities. PPS maintenance is considered relatively minimal but absolutely necessary to ensure permeability and a long lifetime for the system. Dierkes *et al.* (2002b) argued that the infiltration capacity of an almost completely blocked PPS, reduced to below 1mm/(s·ha), was returned to a very high infiltration capacity after cleaning, of between 1545 l/(s·ha) and 5276 l/(s·ha) at three selected points on the surface which were repeatedly measured. The researchers had developed a cleaning device using high pressure of 150 to 300 bars with direct vacuum suction.

3.3 The beneficial effects of PPS on water quality

PPS have not only been established as a SuDS solution, but also as a technology to control pollution collected in runoff from the surrounding impermeable surfaces where contaminated water may infiltrate into the underlying soil (Scholz and Grabowiecki, 2007). Sazaklia *et al.* (2007) concluded that it is highly desirable for harvested rainwater to be used for secondary uses such as watering gardens, indoor and outdoor cleaning, for flushing toilets or even for drinking and cooking purposes. Therefore, the removal of hazardous compounds from the harvested water, whether the pollution is related to microbiological or chemical contaminants, should be taken into account; rainwater should be purified in order to reduce health risks.

The reduction of urban rainwater pollution has therefore become an issue of major concern in order to improve the quality of receiving water. New UK regulations in this regard are explained in section 2.3. The main pollutants of concern in the majority of water quality studies were hydrocarbons, nutrients (nitrogen and phosphorus) and heavy metals, which are defined as the most important harmful substances associated with traffic (Dierkes *et al.*, 2002b), and which have the potential to endanger soil and groundwater resources when they are not sufficiently biodegraded and/or removed during infiltration (Dierkes *et al.*, 2002b; Brattebo & Booth 2003).

PPS have already received the attention of many studies globally, both flow control and as a treatment to improve water quality (Bayon *et al.*, 2005). The infiltration through PPS has been shown to decrease concentrations of several heavy metals and suspended solids (Pratt *et al.*, 1989; Pratt *et al.*, 1995; James and Shahin, 1998; Brattebo & Booth, 2003). According to a number of studies carried out in Australia (Booth *et al.*, 2003; Fletcher *et al.*, 2003; Melbourne water, 2005), if PPS are installed correctly and are well maintained, they can remove up to 80% of copper, 60% of phosphorus, 80% of nitrogen, 70% of heavy metals and 98% of oils and grease in the stormwater. In another related study by Fassman (2012), it was concluded that permeable pavement could reduce by up to two thirds of the runoff contaminant concentrations, such as total suspended solids and total zinc, from typical urban source areas such as road and parking lot surfaces. A related laboratory study by Dierkes *et al.* (2002b) evaluated the heavy metal reduction efficiencies of four pavements: concrete pavers with open infiltration joints, concrete pavers with greened joints (topsoil fill with planted grass), permeable concrete pavers, and permeable concrete pavers with greened joints. While all four pavements retained cadmium, copper, lead and zinc to some degree, systems with permeable concrete or greened joints demonstrated higher pollution retention capacities. The permeable concrete pavers with greened joints had the highest pollutant trapping efficiency. Lead and copper were retained more effectively than cadmium and zinc. Specific removal values were not published by the authors of the study.

Brattebo & Booth (2003) examined the effectiveness of PPS as an alternative to traditional impervious asphalt in a parking area. The results obtained after 6 years of daily use of the system indicated that the infiltrated water contained significantly lower concentrations of heavy metals in comparison with the runoff from asphalt. The results showed metal concentrations even lower than the detection limits that had been assumed, namely: motor oil, 0.10μg/l; diesel fuel, 0.05μg/l; copper, 1.0μg/l; zinc, 5μg/l; lead, 1μg/l. The researchers reported that motor oil was detected in 89% of samples from the asphalt runoff, but not in any water samples that had infiltrated through the permeable pavement. Also, it was observed that runoff performance was very good; all the rainwater was infiltrated through the PPS even during the most intense storms experienced during the study period. The long-term evaluation of PPS performance concluded that its efficiency from the perspectives of mechanical durability, infiltration, and water quality was positive (Brattebo & Booth, 2003).

A PPS test rig was designed by Jayasuriya *et al.* (2007) for a laboratory scale experiment to estimate improvements in infiltrated storm runoff water quality. The results were similar to those of Brattebo *et al.* (2003), mentioned above, since suspended solids, total nitrogen, total phosphorus, copper and lead concentration levels were reduced. However, Jayasuriya *et al.* (2007) reported that the concentration of zinc was more than the input concentration for the first two trials, which could be related to the leaching of zinc from the galvanized metal pavement structure since the rig was constructed in a steel box. Leaching of the coated metal can also occur when collecting rainwater from the roof of a building or from a house via gutters and downpipes, especially since collecting rainwater from roofs is a common strategy. Roofs can be constructed with many different types of material. Rainwater gutters and associated pipes often consist of zinc-coated sheets or copper. The roof area and the material used in constructing the roof influence the efficiency of rainfall collection and water quality. Zinc and copper roofs, or roofs with metallic paint or other coatings, usually show high concentrations of heavy metals in the corresponding runoff if not cleaned prior to discharge (Dierkes *et al.*, 2002a), so they were not recommended by either Abdulla & Al-Shareef (2009) or Helmreich & Horn (2009). The other factor that can influence the harvested rainwater is the type of catchment area (Zhu *et al.*, 2004) and the type of water tank (Pratt *et al.*, 1995; Evison and Sunna, 2001). In an experimental study set up by Aziz *et al.* (2008) different aggregates, for example limestone, gravel and crushed bricks, were shaken with different heavy metal solutions at various pH values. It was found that at pH of 8.5, limestone rendered the highest percentage of metal removal. 90% of most metals was removed from the flask containing the limestone, followed by 80% and 65% rates of removal using crushed bricks and gravel, respectively. Results indicated that the removal of heavy metals was influenced by the media and not directly by the pH. Similarly, a field experiment was carried out by Pratt *et al.* (1995) using a block based PPS with different sub-base stone types such as gravel, blast furnace slag, granite and carboniferous limestone; these were covered by geotextile under the bedding gravel and the concrete blocks. They reported that lead showed very high levels in the outflow, specifically from the sub-base filled with blast furnace slag stone, due to the lead associated with the stone itself. These results enhance the concept that water quality can be influenced upon the type of sub-base stone used in the construction. It is worth considering that pollutant removal rates are dependent upon the material used for the pavers and sub-base material, as well as on the surface void space (Pratt *et al.*, 1989; Fach and

Geiger, 2005). It is therefore important to take into account these studies when evaluating permeable pavements.

Summary

The PPS is designed for rainwater to soak through joints and laying material. The system consists of concrete blocks laid on the surface of the system with gaps in between them to allow rainwater to infiltrate; a layer of clean stone; an overlapping geotextile membrane; the sub-base which is laid in layers containing crushed stone with spaces in between for water storage; and the layer at the bottom is a compacted sub-grade in case the system was designed as an infiltration system, otherwise an impermeable membrane can be placed under the sub-base for the benefit of utilizing the harvested rainwater. The high rate of infiltration is well documented in the literature; it was proved through a number of different experiments set up in labs or at parking lots and focusing on the PPS hydrologic response, specifically how rainwater infiltrated through the underlying drains in the PPS subsurface helping in attenuating peak discharges by reduction in outflow volume and peak flow rate, and delaying the time to peak flow.

Since rainwater stored in the PPS can be used for car washing, toilet flushing, and watering gardens, the removal of hazardous compounds in order to reduce health risks became essential. Many studies in the literature presented PPS as a pollution control technology due to the decrease of heavy metals and suspended solids concentrations through the infiltration process. PPS ability in improving infiltrated runoff water quality is presented in this chapter (section 3.3). The potential of the material used in constructing roofs for influencing rainfall quality is examined in the same section.

The PPS in this research was integrated with a renewable energy system. The next chapter outlines an overview about the REs suitable for domestic use for air conditioning.

Chapter 4 : Renewable Energy

Introduction:

In the last two chapters key issues discussed in the literature on SuDS in general and about PPS in particular, and their role in mitigating environmental problems caused by runoff were presented. In this chapter, the necessity of using natural resources for heating and cooling purposes in order to protect the environment by using Renewable Energy (RE) is presented. The inevitability of introducing RE as an alternative to fossil fuel, the different options of RE that can provide domestic buildings with heating and cooling applications, and their contribution in reducing CO_2 emissions are outlined in this chapter. Also, the UK government's approach and the adopted policy measures towards RE are highlighted.

There is a growing momentum and effort towards producing a cleaner environment and RE sources have become increasingly central to this. They have the potential to play an important role in providing sustainable energy since they are derived from natural processes that are replenished constantly such as sunlight, wind, waves and the tides, plant growth and geothermal heat, which are all 'renewable'. These natural resources offer an alternative to fossil fuels and can help in generating electricity (from wind and tide) and in being a source of heating (from sunlight or solar energy, burning biomass, and geothermal heat) without adding to a net contribution of CO_2 to the atmosphere. RE sources currently supply somewhere between 15% and 20% of total world energy demand. The following section presents green energy options for domestic and residential settings to mitigate the impact of the fossil fuel problem.

4.1 Renewable options for domestic buildings

Reducing energy use in buildings is a critical component of meeting carbon emission reduction commitments. For instance, the fact that residential and commercial buildings in the US use nearly half (48.7%) of all the energy produced in the country is a clear indicator of the dimensions of the issue (Mazria, 2008). On a global scale, the International Energy Agency (IEA, 2006a) reported that the built environment sector consumes 35.3% of the world final energy demand, of which 75% is for inhabited space and domestic water heating. Given these percentages of energy consumption, as well as the impact of the use of fossil fuels that was discussed in Chapter One, it is clear that in order to achieve a considerable reduction in global energy consumption, measures for addressing home energy use should now involve introducing RE sources as an option for houses cooling/heating system (Seyboth *et al.*, 2008; IEA, 2011). In the context of domestic buildings, there is an array of technologies to contribute to the reduction of CO_2 emissions such as biomass, geothermal and solar energy to provide hot water. The use of RE systems for both domestic and industrial / commercial space heating and cooling applications has received relatively little attention compared with, for example, renewable mains electricity and lighting. Currently RE sources provide only 1% of the UK's total heat demand. To reach the 2020 RE target, around 12% of the UK's heating requirements needs to be obtained from renewable sources, which will help increase annual energy savings (Gonzalez *et al.*, 2012), and also reduce CO_2 emissions (Blum *et al.*, 2010). Where a good biomass, geothermal or solar thermal resource exists, heating technologies can often be competitive alongside those traditional systems that are based on the burning of fossil fuels. These resources are amongst the lowest cost options for reducing both CO_2 emissions and fossil fuel dependency.

The largest contribution to RE is the use of traditional biomass burnt in a stand-alone stove, playing an important role in providing house heating particularly for the large populations in developing countries (IEA, 2006c). Biomass heating commonly depends on the burning of wood to provide heat and hot water. It includes wood chips, residues from foresting or wood processing, purpose-grown energy crops (poplar, willow, eucalyptus), agricultural crop and animal residues. Providing domestic buildings with heat by burning biomass is in contrast with the burning of fossil fuels as the biomass takes carbon out of the atmosphere while it is growing, and only returns it as it is burned so that it maintains a closed carbon cycle with no increase in atmospheric CO_2 levels. However, to maintain the sustainability of this system new plants have to continue to grow in place of those used for fuel. Biomass is an affordable heating method since the wood and other material used as the energy source is usually cheaper than fossil fuels , there are available resources distributed over wide areas, and the users of biomass alternatives can benefit from the Renewable Heat Premium Payment and the Renewable Heat Incentive (Gao and Li, 2008; Energy Saving Trust, 2012). However, the main argument against biomass heating is that even though it is a carbon-neutral energy carrier, it does release atmospheric emissions due to the short-cycle carbon loop (Figure 4-1). Other arguments are focused around the energy used for the processes of planting, harvesting and transporting as in some circumstances it requires more energy than it is worth to achieve a net energy gain. Also, plantations usually lead to increased consumption of water, and fossil fuels are used to make the fertilizers employed in the process of cultivating the biomass. Furthermore, extensive use of biomass fuels in the residential sector releases carbon monoxide, hydrocarbons and particulate matter, which may lead to poor indoor air quality and related adverse impacts on health (Fullerton *et al*., 2009; Martínez *et al*., 2012). Finally, the major disadvantage of utilising burning biomass heating systems in domestic buildings is that they are not able to provide any cooling.

Figure 4-1: A typical biomass carbon cycle
(Source: The Carbon Trust, 2009)

Another principal RE system is solar energy, which can be absorbed by a surface solar thermal collector to provide space and water heating at low temperatures. Solar water heater installations can compete with conventional heating fuels in terms of efficiency and cost-effectiveness (IEA, 2012). Such systems operate by circulating water or another heat transfer fluid through a duct heated by transfer from direct solar radiation on a collector panel. The main role of the glazed surface panel is to concentrate the solar radiation on the fluid duct and to maximize solar gains. The glazed surface allows light in and prevents heat loss. The back and sides of the solar panel are thickly insulated. The amount of heat energy provided per square metre of collector surface area varies with design and location, but typically can range from 300 - 900 $kWh/m^2/yr$ (IEA, 2011). Well insulated systems can collect useful amounts of heat even on relatively cloudy or cold days, although a back-up boiler is typically required for periods of very dull weather, which results in a longer payback period for the system.

Barriers to the system's deployment in some situations include planning constraints on roof installations, high up-front capital costs, and a shortage of skilled installation technicians. Naturally, solar heating systems should really only be installed where sufficient sunlight occurs. Lloyd and Kerr (2008) stated that satisfactory thermal stratification by solar energy may not be always achieved in practice due to a number of factors, for example when hot water draw-off occurs either in the evening or early morning, as the back-up or boost will turn on and heat the water in the storage tank by the time the sun is high enough in the sky to allow solar collection. In other words, the solar energy is unfortunately not being supplied during those parts of the day when demand for hot water is highest. Lloyd and Kerr (2008) also concluded that the performance of solar heating was disappointing when compared with heat pump water heating; this result however, was due to insufficient direct sunshine during the study. The use of auxiliary controllers (on/off timers) to prevent the back-up gas or electric heating system coming into play during the daytime made a significant difference to the amount of useful solar energy gain obtained in some situations (IEA, 2006b), but does add to the overall system cost leading to an extending of the payback period.

A third RE option is geothermal heat, an inexhaustible source that has an extensive global distribution, and is independent of weather, season, or energy demand patterns. The efficiency and cost-effectiveness of geothermal energy can be achieved by employing ground source heat pumps (GSHPs), one of the most recognizable RE applications currently in use (Lund *et al.*, 2004; Curtis *et al.*, 2005). In contrast with solar energy panels, GSHPs use the heat that becomes stored up in the ground during summer time, thus they are neither affected with the absence of the sun during night time nor require an artificial storage element. GSHPs can also provide cooling for a domestic or industrial building in contrast with biomass heating system, which can only provide heating. GSHPs have been widely acknowledged as an alternative to fossil fuel systems as they offer a very significant reduction in CO_2 emissions when applied to the cooling and heating of buildings. Systems employing GSHPs are already playing a leading role in reducing global warming and GHG emissions (Healy & Ugursal, 1997; Esen *et al.*, 2006; Saner, 2010). The GHG reduction that can be achieved through applying

GSHP is demonstrated in further details in Chapter Five. In the following section the UK government's approach to renewable energy is discussed.

4.2 The UK government's approach towards RE

Following the Royal Commission on Environmental Pollution report in 2000 (Blundell, 2000), the UK government set a target of a 60% reduction in carbon emissions lower than the baseline 1990 level by 2050 and has since increased the target reduction to 80% (UK Parliament, 2008). This target will require more effort than maintaining stable overall levels of consumption over the years in the domestic and non-domestic sectors. Domestic settings are the focus of this current study since they can play an important role in reducing carbon emissions (households alone contribute approximately 30% of the UK's CO_2 output) (House of Commons, 2009) and more than 70% of these domestic emissions are the consequence of space and water heating (53% for space heating and 20% for hot water) (CLG, 2007). Using RE sources for dwelling space and water heating can help in reducing these carbon emissions, leading to a significant step towards achieving the 80% carbon reduction target.

Several policy measures have been adopted for a significant reduction in CO_2 from UK housing (CLG, 2008), and a number of recent reports on the potential of local or distributed energy have stressed the importance of microgeneration heat technologies. Microgeneration is defined in section 82 of the Energy Act 2004 as the small-scale production of heat and/or electricity from a low carbon source including solar thermal hot water, heat pumps and biomass heating systems (Energy Act, 2004). In 2007 the European Commission set the UK a target of 15% of energy (electricity, heat and transport) to come from renewable sources by 2020, including small scale, low and zero carbon microgeneration systems in domestic and other buildings. Furthermore, The Carbon Vision Building programme (The Carbon Trust, 2004) set a target of 50% carbon emissions reduction from UK buildings by 2030. The Energy White Paper of 2007 committed the UK government to providing support for low-carbon technologies, and encouraging energy saving in the domestic sector through better information, incentive and regulation (BERR, 2007). The Clear Skies programme was a funding scheme set up by the government in order to assist in giving the technology official recognition, and with the aim of establishing regulations governing the registration of credible installers, standards and specifications for heat pumps suitable for the UK domestic sector. However, this programme has been replaced with The Microgeneration Certification Scheme (MCS). The MSC scheme is owned by the department for Business, Enterprise and Regulatory Reform (BERR) (formerly the DTI (Department of Trade and Industry)). It is designed to certify the microgeneration technologies used to produce electricity and heat from renewable sources, providing greater protection for consumers and ensuring that the UK government's (i.e. taxpayers’) grant money is spent in an effective manner. A number of other recent strategy documents aim to reduce CO_2 from this sector by almost 30%, with a projection that by 2020 up to 7 million homes will have received eco-upgrades, including measures such as solid wall insulation, higher air-tightness (with controlled ventilation) and heat pumps (DECC, 2010). The UK Low Carbon Buildings programme supports heat pumps with a grants scheme and the *PowerGen* utility has launched a 1,000-house programme. By applying these programmes it is expected that there will be significant growth in interest and many successful installations of geothermal heat pumps in the domestic sector throughout the UK. Local authorities have a responsibility to ensure there are advice centres, to help householders make changes. For example, energy efficiency improvement is now a condition of planning permission applications and many modern Energy Service Companies are being set up. A heat pump coupled to the current UK electricity grid, for example, will lead to overall reductions in CO_2 emissions of over 50% compared to conventional space heating technologies based on fossil fuels. As the amount of CO_2 emitted by electricity generation falls, so the reduction in CO_2 emissions through the use of GSHP will increase.

Also in the UK, a reduced VAT of 5% is charged on certain energy-saving materials (including GSHP) if these are used for non-business applications (EuroACE, 2009). Heat pumps are an eligible technology for the proposed Renewable Heat Incentive (RHI) programme which is designed to provide financial support (this scheme was expected to come on-stream in April 2011, but the programme is not yet ratified). It is uncertain that this scheme will be ratified in its original form by the present coalition government, but nevertheless it is still anticipated that some sorts of support for low-carbon heat generation will be offered. Therefore it is confidently expected that heat pumps will play an increasingly important part in the UK domestic sector as a retrofit low-carbon technology (Singh *et al.*, 2010). Subsidies, such as the UK low carbon buildings initiative, can make the capital costs more affordable. So far, there seems to have been relatively little uptake of heat pumps in the UK, especially in the residential sector. High up-front capital costs for installing the systems and utility bills covering the electricity consumed during the system's operation rise up as barriers to GSHP up-take. Government support to individuals can be a significant help. Hence, when RHI is considered, as well as the Feed-In Tariffs scheme (FITs) which pays ordinary energy users for the renewable electricity they generate, the two schemes can make adopting GSHP linked to a renewable electricity generator more affordable. The FITs applies for cases of production of electricity from REs (Cansino *et al*., 2010). The RHI or the FIT income received by domestic users and other income tax payers will not be taxed.

Architects and developers are also finding that new assessment criteria for buildings are beginning to take account of the carbon performance of new properties. Furthermore, a study undertaken by the IEA in the UK looking towards a much higher market penetration for heat pumps indicates that the office and retail sectors are key areas for growth and should be the focus of further development (IEA Heat Pump Centre, 2002).

Summary

This chapter highlighted the impact of burning fossil fuels for the purpose of providing comfortable conditions in inhabited space in the domestic and commercial sectors. It is widely accepted now that burning fossil fuels releases emissions of greenhouse gases like CO_2 into the atmosphere, resulting in serious environmental pollution problems. To overcome this problem, using efficient and effective alternative sources of energy is critical. RE sources appear to have the potential to play an important role in providing sustainable energy since they are derived from natural resources and do not add to the carbon in the atmosphere. Geothermal heat is one of the principal RE resources and can be tapped by implementing GSHPs. In the current research, GSHP was the chosen method for the purpose of heating a domestic setting because of their advantages over the other RE systems: GSHP operation is independent of weather, season, and the absence of the sun during night time as the system utilises the constant temperature of the ground, and can provide cooling as well as heating (in contrast with biomass). The focus of applying an efficient heating/cooling system was set up in this study for domestic settings rather than non-domestic buildings. The reason for this is that the domestic sector is responsible for a higher percentage of GHG emission than the non-domestic sector, so achieving energy savings and emissions reduction in this sector will have a much greater impact. Providing heating and cooling to domestic buildings is responsible for almost 35% of UK CO_2 emissions, while non-domestic buildings account for 12%. Hence, providing dwellings with highly efficient heating/cooling systems can play a significant role in helping the UK government to achieve the set targets, and make a significant contribution to sustainable energy development.

A regulatory system offering incentives such as RHI and FITs for domestic installations and making electricity supply cheaper to the users of greener heat can help in reducing the GSHP initial installation costs. Supporting schemes and several policy measures were put in place by the UK government in order to achieve the target of 80% reduction in carbon emissions by 2050. The generalized increase in energy costs and the obligation of decreasing greenhouse gases are factors that will lead to increased interest in using GSHPs in heating systems.

Chapter 5 : Ground Source Heat Pumps

Introduction:

A general presentation of some principal RE sources and the UK government approach towards exploiting them was given in the previous chapter. This chapter will focus on the RE system deployed in combination with the SuDS technique, namely ground source heat pumps (GSHP). In this chapter the key aspects of GSHPs, their potential to provide heating and cooling with high efficiency, and the environmental and economic benefits are addressed.

GSHPs are an alternative to conventional methods for heating and cooling purposes that work either by extracting thermal energy from the ground or by transmitting excess heat into it. GSHP applications are one of three categories of ground energy resources as defined by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE, 1995a). These categories are: (1) high-temperature (>302°F (>150°C)) electric power production, (2) intermediate - and low - temperature (<302°F (<150°C)) direct-use applications, and (3) GSHP applications (generally <90°F (<32°C)). GSHP applications are, thus, distinguished from other ground energy applications since they operate at relatively low temperatures. During winter months, the ground is at a higher temperature than the outside air and therefore GSHP utilizes the ground temperature (low heat reservoir) as a heat source in the heating mode and transmits it into the building. In summer, the ground is at a lower temperature than the outside air and, therefore the system reverses in cooling mode so the 'Earth' itself or a body of water acts as a heat sink (low heat reservoir) (Healy & Ugursal, 1997; Hepbasli, 2005; Nordell *et al.*, 2007; Ozgener and Hepbasli, 2007; Singh *et al.*, 2010). The ultimate source of this latent heat is the sun, which replenishes heat in the ground by direct radiation and by conduction through the air.

Considering that 46% of the solar energy that reaches the planet (total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules/year (renewable-energy-info.com, 2010)) is absorbed by the Earth, it would seem imperative that feasible and sustainable options for utilizing this vast source of free energy for heating applications be used. The surface of the planet receives a massive amount of solar energy that in one year is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, and gas (GCEP, 2011). Omer (2008) and Chiasson (1999) pointed out that the relatively constant temperature in the Earth's subsurface is the result of a complex interaction of heat fluxes from above (the sun and the atmosphere) and from below (generated by the slow breakdown of radioactive elements, and the immense gravitational pressures acting on the rocks and minerals of the Earth's interior) (Figure 5-1 (a) & (b)). Singh *et al.* (2010) confirmed that the subsurface temperature profile coupled with the large thermal storage capacity of the ground can be used as the heat source for domestic heat pumps. GSHPs were defined by Curtis *et al.* (2005) as an established technology capable of providing high efficiencies for heating and cooling, and employing the enormous renewable storage capacity of the ground, available on-site in massive quantities. Lund *et al.* (2004) stated that GSHPs are considered a sustainable technology as they reclaim and recycle thermal energy from the Earth.

Figure 5-1: (a) Solar energy distribution; (b) Geothermal heat comes from pressure and nuclear reactions at the earth's core

(Sources: a) Threshold energies Corporation (n.d); b) Ever source technology development, 2012)

GSHP systems are also known as Geo-thermal Heat Pump, GeoExchange, Water-source heat pumps, Earth-coupled heat pumps, or Ground-coupled heat pump systems. The concept of GSHP is, however, not new at all. Lord Kelvin first developed the concept of heat pumps in 1852, and since then

GSHPs have become one of the fastest growing types of RE in the world. Most of the installations occur in North America, Europe, and China. The number of countries with GSHP installations increased from 26 in 2000, to 33 in 2005, and to 43 in 2010 (Lund *et al.*, 2011). In conventional GSHP installations, coils are buried in a heat source medium, which could be the ground itself or a body of water (pond-type installation). The performance of a GSHP depends on soil type and also improves as moisture content increases (Fan *et al.*, 2007; Zhao *et al.*, 2008); thus, saturated or water environments are preferred. Leong *et al.* (1998) demonstrated that changing the parameter of soil moisture content from complete dryness to 12.5% saturation strongly increases the GSHP performance and vice versa. The finding that relatively wetter conditions have a positive effect on the performance of a GSHP has been supported by results obtained in several other studies (Li *et al.*, 2005; Tarnawski *et al.*, 2009). Based on this, the GSHP in the current research was combined with a tanked PPS which is recharged with rainwater runoff. GSHP injection and extraction of thermal energy is obtained through rainwater being held in the tanked PPS (this will be explained in more details in the following sections).

GSHP systems are increasingly deployed for heating and air-conditioning in commercial and institutional buildings as well as in residential buildings (Ozgener and Hepbasli, 2007). Geothermal International Ltd., UK a company that designs and installs heating and cooling systems reported that GSHPs are now widely accepted as an established technology with approximately 1 million domestic and commercial units installed annually world-wide (Geothermal International Ltd., 2010).

5.1 Description of GSHP

There are three main components to a GSHP; presented in Figure (5-2):

1- The Earth connection.
2- Heat pump.
3- Heating/cooling distribution system.

Figure 5-2: Components of GSHP

(Source: EPC, 2012)

1- The Earth connection:

A GSHP is capable of moving heat from one place to another via the Earth connection, which is also known as ground heat exchanger (GHE). The GHE is comprised of lengths of sealed pipe buried in the ground, or submerged in an underground water reservoir or in surface water, that are used as a heat source and a heat sink. The GHE in this research is buried underground, but harvested rainwater is the surrounding transfer medium rather than soil. This approach was followed to complement the design of a tanked PPS and to form a combined system. Here, the GHE is submerged in water in order that advantageous heat fluxes and heat exchange may occur throughout the combined system. Even when water is in the form of ice or snow it can still produce almost constant values in the extracted heat; this was explained by Tarnawski (1989), Leong *et al.* (1998) and Ling and Zhang (2007) who stated that the heat transfer is dominated by contact between the loops and the frozen surrounding medium due to a very high value of latent heat released once the freezing point of water or soil moisture is reached. This argument was also developed by Bakirci (2010) who reported on the performance of GSHP in reducing primary energy usage in building heating in harsh climates. Tarnawski (1989) stated that snow cover and the freezing of soil moisture around the coil has a positive effect on the efficiency of GSHPs; it was also stated that burying a coil very near the soil surface when the snow cover is stable and thick is recommended for better performance; in unstable snow conditions, deeper coil is recommended. Hence, the concept of immersing the exchanger of the GSHP in a PPS tanked system could be significantly advantageous but is not an approach which has been investigated before.

The GHE is composed of high-density polyethylene (HDPE) piping with a diameter ranging between 20-40mm. The length and width of the loops is determined by the ground conductivity properties. The most important variables are the type of soil (including temperature, moisture content, particle size and shape, and heat transfer coefficients), the local geology and the area of available land for such installations (Leong *et al*., 1998; Saljnikov *et al*., 2007). Using the right pipe material and joints can provide reliable leak resistant loops that can be installed without requiring any maintenance for up to 50 years (Rawlings and Sykulski, 1999). The GHE can be set in one of the following approaches (Figure 5-3):

- Vertical, for use in boreholes; referred to as borehole heat exchanger (BHE)
- Horizontal, for use in trenches
- Spiral, coiled or 'slinky', also for use in trenches or ponds.

These designs of GHE are subject to local environmental conditions, installation costs and the conductivity of local soils.

Figure 5-3: Different GSHP designs existing in practice

(Source: Synergy Solar Solutions, 2011)

The GHE can be grouped into two types: closed-loop and open-loop systems (Figure 5-4, a & b). For the closed-loop systems the pipe is usually a closed circuit and is filled with an antifreeze solution that is pumped to circulate through these pipes and acting as a thermal carrier (Ozgener and Hepbasli, 2007), allowing heat, but not fluid, to be transferred from the building to the ground and/or vice versa. Open-loop systems are fed by water either from an underground aquifer, in the same way as a traditional well, or from surface water bodies i.e. lakes, ponds, sea and then circulating the drawn water to the heat pump and subsequently discharging it (Curtis *et al.*, 2005; Lee, 2009).

a) Closed loop heat pump systems

b) Open loop heat pump system

Figure 5-4: Types of GHE, a) Closed loop system; b) Open loop system

(Source: Geo-heat Center, 2012)

Based on these principles, and since a typical design procedure of GSHP would involve first selecting the suitable system for the building, the closed-loop system was the choice for this study since there was no surface water available near the study area. However, even if there had been a water source at the site, it was borne in mind that the focus of this research is *domestic* buildings, and as the vast majority of dwellings are located distant from water bodies, therefore it made more sense to select a system that did not rely on the availability of a water source but that instead suited the conditions found in the locations of the majority of houses. Thus, a closed-loop system was selected to fulfil the research purposes.

According to the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE, 1997), GSHP systems can be grouped into three categories based on the heat source/sink used to distinguish among the various types of Earth connection systems. These categories are:

1- Ground-water heat pump (GWHP) systems,
2- Ground-coupled heat pump (GCHP) systems, and
3- Surface water heat pump (SWHP) systems.

Each of these types is discussed in the following subsections.

I. Ground Source Heat Pumps (GSHP)

A GSHP is a closed-loop system that exchanges heat with the Earth via pipes buried in either of two ways: a series of deep vertical boreholes or a horizontal arrangement of pipes buried a few metres below the surface in a trench. The choice depends on the available land, local soil type and excavation costs (Rawlings and Sykulski, 1999).

When using the borehole method, one or more 100 to 150mm diameter holes are drilled to a depth of 15 to 150m. In each hole, a pipe leads down and then loops back up to the surface, providing as much surface area as possible for heat transfer to take place. With deeper holes, problems can occur with backfilling, static pressure and insertion of the heat exchanger (Rawlings and Sykulski, 1999). The advantages of vertical GHEs are that they require relatively small ground surface area and can yield the most efficient system performance (Diao *et al*., 2004). When using the buried trench method, one or more trenches are excavated to a depth between 0.5 to 2m. Horizontal GHEs are generally more appropriate for average-sized buildings such as residential and small commercial buildings. However, this type of heat exchanger layout could be criticised for a number of reasons, such as, longer pipe lengths required than for vertical wells, and antifreeze solution viscosity increases required pumping energy, decreases the heat-transfer rate, and thus reduces overall efficiency (Omer, 2008). Additionally, horizontal GHEs require a relatively large area free from hard rock or large boulders. A spiral or slinky coil, whereby pipes overlap can reduce the surface area required for horizontal earth connections; this type of layout is common in PPS applications, especially in cases of limited land availability (Wu *et al.*, 2010; Fujii *et al.*, 2012). The overlapping configuration reduces the amount of land needed, while increasing the heat transfer by increasing the amount of contact with the ground by more piping per length. For these reasons, a slinky coil in a horizontal trench was the method that was applied for the purpose of this study involving an average-sized house. However, there are some disadvantages in the use of a slinky coil: they require more total pipe length when compared with horizontal GHE designs; they require a relatively large ground area; ground temperature are subject to weather and air temperature fluctuations; larger pumping energy requirements than for horizontal GHE pipes (as explained above); and backfilling processes could damage the pipe system (Omer, 2008). The other solution for limited space issues could be implementing a horizontal double tier ground loop instead of a single tier (Figure 5-5, a & b) (Singh *et al.*, 2010; Wu *et al.*, 2010); this can reduce the surface area required for the ground loop by 50%.

Figure 5-5: Ground loop pipes arrangements: (a) single tier; (b) double tier (Source: Singh *et al.*, 2010)

Due to the shallower depth required by the horizontal GHE when compared with a vertical GHE, the former is less expensive to install. This particular fact was also taken into consideration when a horizontal ground-loop was chosen for the heating/cooling system to be monitored. It is more likely that the cost of installation would be a concern that house owners and/or builders would consider at the initial phase of planning the construction. When a GSHP is compared with a groundwater heat pump system (which is explained in further details in the following section), it has the advantage of eliminating the problems associated with ground water quality and availability. Furthermore, they generally require much less pumping energy than water well systems because of their shallower depth.

II. Groundwater Heat Pumps (GWHP)

GWHP and surface water heat pump (explained in the following section) systems are not the focus of this thesis, so they will only be briefly described here.

GWHP are the original type of GSHP system. They are, in contrast to GSHP, open-loop systems which use a constant supply of groundwater as the heat transfer fluid (see Figure 5-6). In this system conventional water wells and well pumps are used to supply groundwater from an aquifer to a heat pump (Yang *et al.*, 2011). The pumped water is used as the heat transfer fluid which provides heat to the building after gaining more heat via the heat pump (the process of heating fluid through the heat pump is explained in the following section). After leaving the building the 'used' groundwater is typically discharged to a suitable receptor, such as back to a well, or, where permitted, discharged into a stream or river (Nam and Ooka, 2010). The disposal method should be taken into consideration at an initial stage of the design. However, with growing environmental concerns over recent decades, extracting and re-injecting groundwater might be subject to certain environmental protection measures and legislation (Omer, 2008).

The main advantage of GWHP systems is their energy efficiency, low maintenance cost, simplicity, and small amount of ground area required relative to other GSHP and conventional systems (Chiasson, 1999; Yang, *et al.*, 2011; Verda *et al.*, 2012). However, the cost of power required for pumping the water could be prohibitively expensive when the water table is especially deep-seated (ASHRAE, 1997). Also, corrosion protection of the heat pump may be necessary if ground water chemical quality is poor.

Figure 5-6: Ground water heat pump - Open loop
(Source: Geo-Heat Center, 2012)

III. Surface Water Heat Pumps (SWHPs)

There are two types of surface water heat pumps: closed-loop and open-loop (Figure 5-7). Typical closed-loop configurations are the series of coiled pipes type (slinky coil), or the loose bundle coil type submerged below the surface of a lake, pond, reservoir, or other suitable open at-surface body of water. In the closed-loop systems, heat transfer to or from a surface water body is accomplished by circulating a heat exchange fluid through an enclosed pipe immersed at an adequate depth within the water body. In open-loop systems, water is withdrawn from the surface-water body, passed through a heat exchanger, and is then discharged to a suitable receptor (Nova Scotia Environment, 2009; Chiasson, 1999). The SWHP is a low cost GSHP option and requires minimal excavation; however, the water body must be sufficiently deep and large (Omer, 2008).

Figure 5-7: Closed-loop SWHP (left) and Open-loop SWHP (right)
(Source: Geo-Heat Center, 2012)

2- The heat pump

Heat pumps can either make use of the outdoor air, known as Air Source Heat Pump (ASHP), or can use the ground as a heat source (GSHP, as used in this current research) for heating and cooling a domestic or commercial building. However, the efficiency of GSHPs is higher than that of ASHPs because even shallow subterranean temperatures are higher than mean air temperatures in winter and lower than the mean air temperatures in summer. The term "ground-source heat pump" has become an all-inclusive term to describe a heat pump system that uses the Earth, ground water, or surface water as a heat source and/or sink. In the same way that a fridge uses refrigerant to extract heat from the inside, keeping food products cool, a GSHP extracts heat from the ground, and uses it to heat buildings. The heat pump transfers the heat between the heating and the cooling distribution system and the GHE. This unit is required to convert the low-grade heat captured in the fluid into suitable high-grade heat for use in the dwelling. Heat pumps use electricity to operate pumps that alternately evaporate and condense a refrigerant fluid to move that heat. In cooling mode, the above process is reversed with the use of a reversing valve, whereas the Earth connection-to-refrigerant heat exchanger becomes the condenser and the refrigerant-to-air heat exchanger becomes the evaporator which takes heat out of the air and thus cools the building (RETscreen International, 2009). The heat pump unit consists of three main parts (the 4th part listed below is not a main part) (Figure 5-8) where a 3-phase cycle is regularly repeated:

I. **The evaporator** - A large quantity of low grade energy absorbed from the ground loop is transferred to the refrigerant. This causes the temperature of the refrigerant to rise, changing it from a liquid to a gaseous state. When the refrigerant flows through the evaporator its low-grade heat is transferred to the working fluid in the heat pump and its temperature is reduced.

II. **The compressor** – when the working fluid flows in the condenser, its heat is transferred to the heating network water; this process happens by using a relatively small amount of electricity to compress the working fluid, reducing its volume and causing its temperature to rise significantly and bringing it to a higher temperature level in order to provide a comfortable heating temperature, in addition to some pre-heating of domestic hot water, in certain cases.

III. **The condenser** - gives up heat from the working fluid to heat the water which feeds the distribution system. After giving up its heat energy the refrigerant turns back into a liquid and can once again absorb energy from the ground, allowing the cycle to begin again.

IV. **Expansion valve** - In cases where a heat pump is concerned with both the cooling effect produced at the evaporator, as well as the heating effect produced at the condenser. In these dual-mode GSHP systems, a reversing valve, known also as expansion valve, is used to switch between heating and cooling modes by reversing the refrigerant flow direction.

Figure 5-8: The heat pump cycle
(Source: VSE a.s., 2011)

Although the cooling mode transfers heat to the Earth, and thus is not geothermal, it still saves energy and thus contributes to a "clean environment" (Curtis *et al.*, 2005). In this way, the heat that has been transferred and accumulated in the Earth during the cooling season can be effectively used during the winter months for inhabited space heating (Banks, 2008). When extracting and rejecting the same amount of heat from and to the Earth through the GSHP's heating and cooling modes, the soil heat loss occurring during heat extraction (in winter) will be complemented by injecting heat while operating in space cooling mode (in summer), so the annual thermal balance of the ground can be preserved. This will maintain an efficient stable performance of the GSHP (Young, 2004; Wang *et al.*, 2010). The climatic conditions in many northern European countries are such that by far the greatest demand is for space heating; air conditioning (in other words 'cooling') is required less, therefore the heat pumps usually operate primarily in the heating mode. In general, there is limited demand for cooling in UK houses (Curtis, 2001). A system of multiple heat pump units can be used for larger commercial, institutional or industrial buildings, however for residential applications a single heat pump unit will be adequate (Sanner *et al.*, 2003). The process of delivering heating or cooling to the building by using the Earth to transfer heat through the GSHP system to the heating/cooling distribution system is presented in (Figure 5-9).

Figure 5-9: Heating and cooling mode using GSHP
(Source: Water furnace, 2011)

3- Heat distribution system

This is the indoor unit, and it consists of under-floor heating or radiators for space heating connected via normal water pipes, and in some cases water storage for a hot water supply. It usually takes the form of an air duct distribution system, although water loop systems (also known as hydronic systems) which heat or cool floors and ceilings are also used. Typically radiator systems need water between 60°C and 80°C, whereas the water circulating in the under-floor heat pipes is no more than 50°C (usually from 35 to 50°C) (Carbon Trust, n.d). Such a low circulating temperature requires radiators with greater surface area. A large area of under-floor heating distributing gentle warmth is more efficient than a small area of radiators emitting high temperatures and causing draughts (Ingram, 2004; ICAX, 2007).

5.2 Energy efficiency of the GSHP

The efficiency of GSHP units is measured by the Coefficient of Performance (CoP) (Tarnawski *et al*., 2009), with higher values being more desirable (the higher the number, the better the efficiency). The CoP in heating mode ($CoP_{heating}$) and the Energy Efficiency Ratio (EER or $CoP_{cooling}$) in cooling mode are the ratios of the output energy divided by the input energy (work done by compressor and pumps = electricity consumption of a heat pump) (Curtis *et al*., 2005). Measuring the CoP, which is part of the current study, allowed the determination of the amount of electricity that can be saved by using a heat pump in order to produce heat, hence enabling calculation of the operating cost of the GSHP based on the electrical energy used during its performance.

The performance of a heat pump is expressed in terms of CoP, defined as (Cengel & Boles, 2011):

$$\mathrm{CoP} = \frac{\text{Desired output}}{\text{Required input}} \tag{1}$$

The heat pump in a constructed system can be assumed to follow a reversed cycle (Carnot cycle), in which the direction of any heat and work interactions of the heat pump cycle are reversed: heat in the amount of Q_L is absorbed from the low-temperature reservoir, heat in the amount of Q_H is rejected to a low-temperature reservoir, and the work input of W_{net} is required to accomplish all this (Wark, 1999; Cengel & Boles, 2011).

Typically, geothermal systems have CoP values that vary between 3 and 4, with values as high as 6 reported in the literature (Lund *et al.*, 2003; O'Connell and Cassidy, 2003). Thus, a CoP of, for example, 3 would indicate that the output of the heat pump is three times the amount of electrical energy input; i.e. the efficiency is 300%; which means that the useful heat output will be greater than the energy required to operate the pump itself. Research has been carried out to determine the performance of horizontal GSHP, as presented in the table below.

Table 5-1: Relevant studies conducted on the heating performance of horizontal GSHP

Author(s)	**Location**	**Application**	**Pipe depth**	**Results and comments**
Metz (1983)	Long Island, New York	104m² house	1.2 m	$CoP_{heating}$ = 2.46
İnallı and Esen (2004)	Elaziğ, Turkey	A room of 16.24 m²	1 and 2 m	$CoP_{heating}$ = 2.66, and 2.81 for the 1 and 2 m depths, respectively
Doherty *et al.* (2004)	Nottingham, UK	Eco-House at University of Nottingham	Horizontal slinky at a depth of 2m	$CoP_{heating}$ ≈ 2.7
			1 m³ of tanked coil	$CoP_{heating}$ ≈ 3.0
Coşkun *et al.* (2008)	Bursa city, Turkey	Test room in the laboratory of Uludag University	GHE was buried at depth of 2 m	$CoP_{heating}$ = 2 - 2.5

A more favourable CoP is achieved through horizontal ground systems compared to air source heat pump systems (Petit and Meyer, 1998), and which ranges between 1.5 and 2.5 (Curtis *et al.*, 2005). This is due to the greater variations that are observed in outdoor air temperatures. The temperature below the ground surface does not fluctuate significantly throughout the day or the year; this is in contrast with the conditions for

ASHPs, which are subject to higher temperature fluctuations because they are dependent on outdoor air temperature (Omer, 2008).

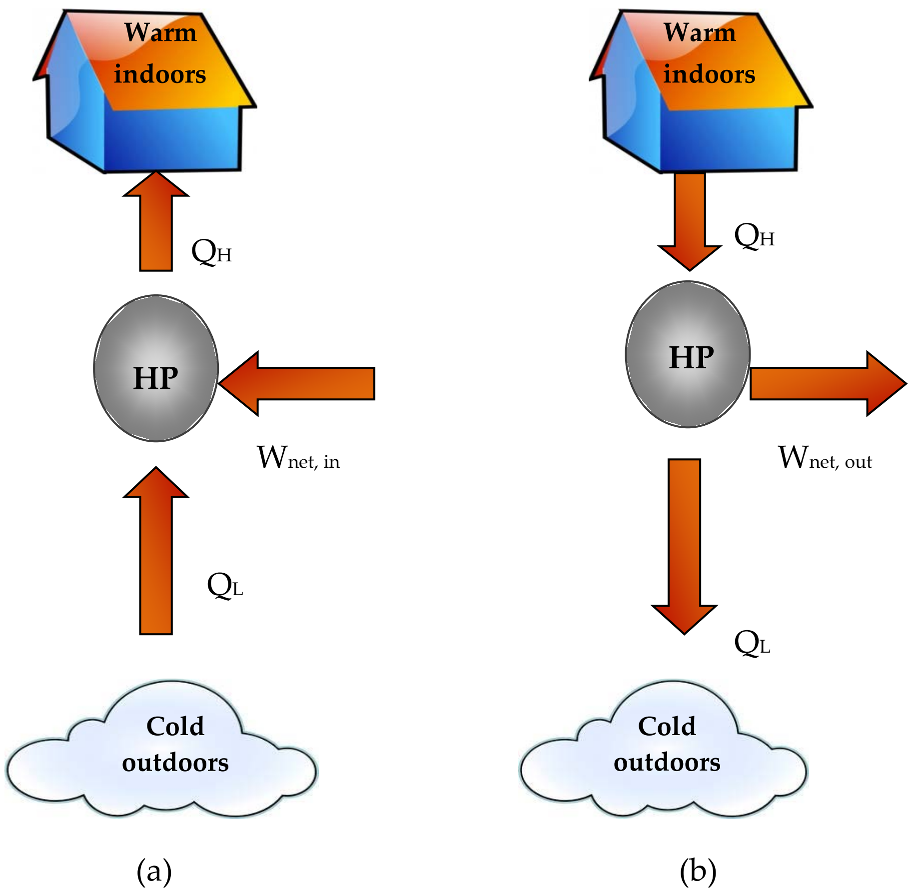

Figure 5-10: A schematic of the direction of heat and work interactions of the pump cycle

(a) Heating mode: The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors. (b) Cooling mode: Part of the heat received by the heat pump is converted to work, while the rest is rejected to a sink

(Source: Adapted from Cengel & Boles, 2011)

$$CoP_{heating} = \frac{Desired\ output}{Required\ input} = \frac{Q_H}{W_{net}} \quad (2)$$

$$\mathrm{CoP_{cooling}}\text{or The Energy Efficiency Ratio} = \frac{Desired\ output}{Required\ input} = \frac{Q_L}{W_{net}} \quad (3)$$

The network input of the system is also equal to the net heat transfer to the system:

$$W_{net} = Q_H - Q_L \quad (4)$$

The smaller difference in temperatures between the heat source and the heating space, the better the CoP or EER (Hepbasli *et al*., 2003; Inalli and Esen, 2004).

By substituting equation (2) with equations (3) and (4)

$$CoP_{heating} = \frac{Q_H}{Q_{H-}Q_L} \quad (5)$$

$$CoP_{cooling} or\ EER = \frac{Q_L}{Q_{H-}Q_L} \quad (6)$$

When the GSHP is operating at a theoretical maximum CoP (this is the Carnot cycle CoP), which is found when the desired heat is provided using the theoretical minimum work (Hepbasli *et al.*, 2003; Hepbasli & Akdemir, 2004; Inalli and Esen, 2004 and Hepbasli, 2005), the following equation applies:

$$\frac{Q_H}{T_{max}} = \frac{Q_L}{T_{min}} \tag{7}$$

Where T_{max} is the temperature of the hot medium (heat supplied), and T_{min} is the temperature of the cold medium (heat extracted).

By substituting equation (7) we obtain:

$$\frac{Q_H}{Q_L} = \frac{T_{max}}{T_{min}}$$

$$\therefore \quad CoP_{heating} = \frac{T_{max}}{T_{max} - T_{min}} \tag{8}$$

$$and,\ CoP_{cooling} = \frac{T_{max}}{T_{max} - T_{min}} \quad \text{(Hepbasli, 2005)} \tag{9}$$

CoP is mainly affected by operating conditions, (Hanova and Dowlatabadi, 2007) such as thermal soil/rock conductivity; thermal and hydraulic properties; the depth, length and type of the ground heat exchanger, type of backfilling material; daily heating and cooling loads; and temperature and flow rate of circulation water through the ground heat exchanger (Zhao *et al.*, 2003; Doherty *et al.*, 2004; Zhao, 2004; Nurdan *et al.*, 2006). These differences decrease at depths below about 10m (Michopoulos *et al.*, 2007; Popiel *et al.*, 2001), as the ground temperature is constant throughout the year and increases slightly with depth beneath the ground surface. Near to the surface, the ground temperature is influenced by the overlying air temperature and the fact that there is less heat coming from the Earth's interior (mentioned above in section 5.0). In very cold climates heat pumps are less effective due to the large temperature difference between indoors and outdoors leading them to operate less efficiently, which is unfortunate as it is precisely in such climates that greater heat generation is required. Due to these conditions, vertical BHEs exhibit better performance and energy efficiency than horizontal GHEs (Petit and Meyer, 1998; Sanner *et al.*, 2003).

In order to enhance the performance of heat exchangers, innovative techniques have been developed, for example, by combining a supplementary source of energy such as solar energy, usually known as solar-assisted heat pump systems, that utilizes both a solar collector and the ground as the heat source (Ozgener and Hepbasli, 2005; Yang *et al.*, 2006; Wang *et al.*, 2010). Another type of hybrid GSHP is one in which the ground heat exchanger size is reduced and an auxiliary heat rejecter (e.g. a cooling tower or some other option) is used to handle the excess heat rejection loads during the cooling operation when applied to a building (Hackel and Pertzborn, 2011). A third variation that utilizes solar heat injected into the ground in winter, and also gives solar domestic hot water production during summer (Kjellsson *et al*., 2010), are water tank coils (Johnson *et al*., 1988; Doherty *et al*., 2004). In the literature there are reports on many theoretical and experimental studies concerning the use of water as a heat source/sink. As an example of these studies, Yumrutas and Ünsal (2000 and 2005) presented an analytical model that was developed for a hemispherical surface water tank as the ground heat source/sink for a heat pump system. Gan *et al*. (2007) examined the performance of a heat pump system designed to make use of rainwater and the ground as heat sources. The previous studies were carried out under laboratory conditions and by means of numerical simulations, but there is no study in the literature based on utilizing rainwater and a GSHP with a horizontal slinky coil in 'real life' conditions, which is the novel aspect of this current research. It is worth pointing out that in the study by Doherty *et al*. (2004), although rainwater was used as a heat transfer medium in a GSHP system, this was for a circuiting copper tube placed vertically in a tank coil system; the slinky coil used in their study was not surrounded with rainwater.

Furthermore, Chiasson (1999) found that a higher CoP can be achieved by a GSHP because heat is absorbed and rejected through water, which is a more desirable heat transfer medium because of its relatively high heat capacity. However, heat pumps are less effective in very cold climates due to the large temperature difference between indoors and outdoors leading them to operate less efficiently.

Using GSHPs for dwelling heating and cooling will lead to less consumption of the existing finite natural energy resources, and thus the potential for releasing less CO_2 into the atmosphere, and there are also economical benefits. Evidence for the environmental and economical benefits of using GSHPs is discussed in the following sections.

5.3 Energy savings

The heating and cooling systems of buildings account for 30-50% of global energy consumption (Ala-Juusela, 2007; Seyboth *et al.*, 2008). In the UK the domestic sector accounted for 32% of overall energy consumption in 2010; most of that energy (61%) was used for domestic space heating with water heating accounting for 18% (DECC, 2011a). DECC (2011b) confirmed that the average annual consumption of energy for heating (comprising of space and water heating energy) per household crept up from 1970 until 2004, but has fallen by nearly 10% since then (up to 2009). This reduction can in turn be attributed to more efficient insulation, smaller home size and warmer winters (Singh *et al.*, 2010). In 2010, on the other hand, the total energy consumption by the domestic sector was 31% higher than in 1970 (13% higher than in 2009) (DECC, 2011a). This was attributed to the rise in the total number of dwellings and the UK population by 1% since 2009 (DECC, 2011a). Statistics on household projections show that the number of households is still going to increase.

The number of households in the UK in 2011 was 26.3 million (Office for National Statistics, 2011); this figure is projected to grow to about 33 million in 2033 (CLG, 2010). More dwellings implies an increase in the number of heating units, resulting in an additional pressure on top of the existing consumption of energy for heating. The built environment was identified by an intergovernmental panel on climate change in 2007 as having both the highest GHG emissions and the best potential for emission reduction (Hughes, 2008; DECC, 2011b). In the United States, for example, heating and cooling account for 40% of total utility consumption (UNEP, 2004), with two thirds of a typical homeowner's energy bill covering heating, cooling and hot water, indicating the potential for reducing utility expenses through increasing the efficiency of such systems.

GSHPs transform 'Earth' energy into useful energy to provide clean and energy-efficient heating and cooling year round. They use less energy than alternative heating and cooling systems, helping to conserve our natural resources. The US EPA estimated that geothermal heat pumps can reduce energy consumption by up to 44% compared to air-source heat pumps (ASHP), and up to 72% compared to conventional electrical heating and air conditioning (US EPA, 1997). Energy saving is even higher when compared with fossil origin fuels or electrical resistance heating systems. The adoption of GSHP systems may result in primary energy consumption reduction up to 60% compared to conventional heating and cooling systems (Michopoulos *et al.*, 2011). In an experiment designed in the context of a European Union Project to allow a fair comparison between the efficiencies of a GSHP system and an ASHP system, the results during the systems' first operational year were that the ground-coupled system saved 41% of electrical energy compared to the air-source system in heating mode, and 38% in cooling mode. The overall seasonal saving is 40% (GeoCool project, 2006). Implementing GSHP also reduces greenhouse gas emissions, which will be discussed in the following section.

5.4 Greenhouse gas reduction

GSHPs have a large potential for contributing to global CO_2 savings. Several authors have reported on the role of GSHP in GHG (particularly CO_2) reduction; Genchi *et al.* (2002) confirmed that a GSHP is a viable option for reducing life-cycle CO_2 emissions, including embedded carbon associated with the construction of the system. In their results they found that the GSHP system would result in a CO_2 reduction of 54% when compared with a conventional ASHP. Fridleifsson *et al.* (2008) estimated about 33–50% savings in CO_2 emissions by using GSHP systems instead of fossil fuel fired boilers. This corresponds with a study by Blum *et al.* (2010), who estimated CO_2 savings of 35% to 72%, depending on the supplied energy for the heat pumps and the efficiency of installation. They showed that in Germany the CO_2 savings for one installed GSHP unit with an average heating demand of 11 kW is at least 1800 kg per year. Omer (2008) reported that GSHP can reduce GHG emissions by 66% or more compared to conventional heating and cooling systems based on fossil fuels. Curtis *et al.* (2005) argued that if the annual geothermal energy use is 28,000 TJ (7,800 GWh), and comparing this to electrical energy generation using fuel oil at 30% efficiency, then the savings are 15.4 million barrels of oil or 2.3 million TOE (tons of oil equivalent). This equates to savings of about seven million tonnes of CO_2.

These results are in line with findings made by O'Connell and Cassidy (2003), who reported that CO_2 emissions savings by using horizontal GSHP systems are estimated to be 30% in comparison to natural gas heating, 45% when compared to oil-fired boilers, and even 100% when utilizing a RE resource for electricity. A comparison of different heating systems is shown in Table 5-2 (Omer, 2008).

Table 5-2: The CO_2 emissions from operating GSHP and other fuel-type conventional heating systems

System	Primary Energy Efficiency (%)	CO_2 emissions (Kg CO_2/kWh heat)
Oil fired boiler	60 – 65	0.45-0.48
Gas fired boiler	70 – 80	0.26-0.31
Condensing Gas Boiler + low temperature system	100	0.21
Electrical heating	36	0.9
Conventional electricity + GSHP	120 – 160	0.27 – 0.20
Green electricity + GSHP	300 – 400	0

The overall potential for GHG reductions is determined by the lifecycle emissions of each energy source, and the efficiency of the energy conversion used to meet heating loads.

Along with the energy savings and the greenhouse gas reduction by using GSHP, there are economic benefits when the system is installed. However, there are a couple of concerns regarding the adoption of the GSHP solutions. The economic benefits as well as the concerns are discussed in the following section.

5.5 Economic benefits and concerns

As the cost of energy continues to rise, it becomes imperative to save energy as well as improve overall energy efficiency. Adopting a source of free heating energy instead of commercial energy can effect a dramatic reduction in energy consumption, followed by financial savings. The awareness of the economic benefits of using GSHPs would enhance the likelihood of these systems being selected to meet domestic heating and cooling requirements (Esen *et al.*, 2006). Joblin (2005) states that schools in the United States spend more than $6.0 billion (nearly £3.4 billion in accordance to the US Dollar to Great British Pound exchange rate in 2005, that is 1$ = £0.56 (www.x-rates.com)) on energy each year; if all schools converted to GSHPs, the 25 to 40% savings estimated would translate into $1.5 to $2.4 billion (equivalent to £0.84 and £1.34 billion). The fact that a GSHP uses 75% less electricity than conventional AC systems further illustrates how economical an option they may be (Omer, 2008). Bose (2005) argued that energy bills for domestic applications can be reduced between 30% and 70% when in the heating mode and between 20% and 50% when in the cooling mode.

Despite the savings that GSHPs can provide, and the fact that they are recognized globally as energy-saving devices, there is still a significant drawback in employing these systems, which relates mainly to the installation cost. O'Brien (2000) stated that the GSHP installation cost is 40% greater than that of oil or gas fired boilers, the most common forms of residential space heating, and 50% greater than for electric storage heaters. The capital costs for a GSHP system are, however, made up of the equipment costs for the heat pump unit, the ground coil and the distribution system, the drilling or trenching costs, and the construction of a BHE (borehole exchanger) or groundwater well also occupies a large portion of installation costs. The highest proportion of the capital cost is for the installation of the ground loop; typically accounting for between 30% and 50% of the total. Even so, the installation costs are typically returned in energy savings in 5–10 years (Kim *et al.*, 2010), varying with capital investment costs and a region's fuel prices, and relative to fuel price increases.

Many energy efficient appliances have higher initial purchase costs, but lead to significant amounts of money being saved because of lower energy costs. This was confirmed by Petit and Meyer (1998) when they studied the economic potential of a GSHP system and an ASHP system under South African climatic conditions. From this study it was concluded that although the capital cost for the ASHP (11,457 South African Rand, SAR equal to ~ £1613, at the exchange rates around the time the study was carried out, October 1996) is lower than that for a GSHP system (27,871 SAR equal to ~ £3924), a GSHP is a more energy-efficient system than an ASHP when techno-economic factors such as CoP (coefficient of performance) and payback periods are taken into account. Esen *et al.* (2006) in an economic analysis compared a horizontal loop GSHP system to conventional heating methods (electric resistance, fuel oil, liquid petroleum gas, coal, oil and natural gas); they demonstrated that the horizontal GSHP system offers economic advantages over the five conventional heating methods. However, it would appear not to be such an economical alternative system to natural gas if the relatively low fuel prices in Turkey at the time of the study were taken into account. Similar conclusions were made by Pulat *et al.* (2009) for the relatively mild climate in Turkey and by Healy & Ugursal (1997) for the cold climate in the province of Nova Scotia in Canada. Desideri *et al.* (2011) concluded in their study that the operating costs necessary to heat a residential building with a GSHP were lower than the operating costs necessary to heat the building conventionally with energy sourced back to a natural gas power plant. The other financial saving from using a GSHP is that the systems are used to provide both heating and cooling, thus potentially saving the cost of both a boiler and cooling equipment. Also, the lifetime of the heat pump would normally be taken as 20 years (Greening & Azapagic, 2012), but the lifetime of the ground coil is expected to be substantially longer, possibly in excess of 50 years, and the system can reasonably be expected to provide reliable and environmentally friendly heating for in excess of 20 years (Ozyurt and Ekinci, 2011).

It could be argued that GSHPs use a renewable heat source, but are not in themselves classed as a RE technology inasmuch that their heat exchangers must be driven by electricity. This raises questions about the running costs when applying a GSHP system which depends on electricity. If the electricity can be generated from renewable sources, such as a wind turbine, in the first place, then all of the delivered energy will be renewable. However, GSHP running costs still are less than for electric resistance heating by about 50% and less than for an ASHP by about 33% (Lienau, 1995).

In order to make GSHPs more attractive, Singh *et al.* (2010) proposed reducing, for example, the costs of drilling and loop installation. Moreover, trenching costs generally are higher than piping costs per linear metre, so systems using multiple pipes in one trench will be more economical (Rawlings and Sykulski, 1999). Also, for GSHPs to gain popularity, manufacturers and suppliers need to embark on an aggressive campaign to spread information aiming to educate the prospective consumers and policy makers about the environmental and cost-saving benefits of heat pumps. This should encourage growth in the market and so eventually lead to a reduction in the initial installation costs. A regulatory system offering incentives (as explained previously in section 4.2) such as carbon credits for domestic installations and making electricity supply cheaper to the users of greener heat might also help in this regard.

Summary

GSHPs have been recognized as a highly efficient system for delivering renewable heat. A GSHP has three main components: the Earth connection, heat pump and heating/cooling distribution system. In order to extract heat or reject heat to the ground, a solution with antifreeze is circulated through pipes (GHE) laid in the ground in either a horizontal (straight pipes or spiral), or vertical configuration. The choice of the pipes layout depends on the available land, local soil type and excavation costs. The GHE can be grouped into two types: closed-loop and open-loop system. Taking into consideration that the focus of this research is domestic settings, the horizontal spiral closed loop GHE was the selected layout to be applied in this study, since they are found to be a more optimally applicable approach for domestic settings when land space and installation costs are considered. The mechanical part of the GSHP is the heat pump. This unit is required to convert the low-grade heat captured in the fluid into suitable high-grade heat for use in the dwelling. Delivering heating or cooling to a building is achieved by transferring the heat from the Earth through the heat pump to the heat distribution system. Under-floor heating distribution was chosen to be installed at the dwelling monitored for this research since this type provides gentle warmth and is more efficient than a small area of radiators emitting high temperatures and causing draughts.

The efficiency of GSHP units is measured by the CoP. Typically, geothermal systems have CoP values that vary between 3 and 5. A GSHP CoP is higher than that of an ASHP. The temperature below the ground surface does not

fluctuate significantly throughout the day or the year, which is in contrast with the conditions for ASHPs. Calculating the CoP, which is the procedure applied in this study with results given in Chapter Eight, allows for estimating the amount of electricity that can be saved by using a heat pump in order to provide heating to a building. Higher CoP values are more desirable (the higher the value, the better the efficiency).

GSHPs have established themselves as one of the most powerful and cost-effective tools to contribute to a secure energy future. More importantly, their role could be significant in carbon reduction. Replacing fossil fuel heaters with GSHPs at dwellings for heating and air conditioning purposes can reduce for individuals their personal average electricity bill and can also help them to become significant contributors to reducing energy consumption, thus acting to preserve our environment by reducing CO_2 and greenhouse emissions. The higher the efficiency of the GSHP is, the higher the environmental and economic benefits are.

Since wetter conditions have been found to have a positive effect on the performance of GSHPs, this study aims to study the feasibility of combining GSHP with tanked PPS. The combined system was installed and monitored under 'real life' conditions at a domestic setting in the UK, namely 'The EcoHouse' at the Building Research Establishment (BRE), which is described in the following chapter.

Chapter 6 : Site Description and Methodology

Introduction:

In the previous chapters, PPS has been put forward as an appropriate sustainable drainage technique suitable for domestic buildings, as it can be used in driveways and/or hard surface front gardens for parking purposes. Their flexibility to be tailored to give a "tanked system" to retain the harvested rainwater for re-use purposes was also highlighted. In continuation, GSHPs were presented as being efficient and green devices suitable for providing heating and cooling for domestic buildings, but possibly more important is the fact that the systems have been demonstrated to perform better in wetter environments. Based on these characteristics, the two systems were combined in this research so that the GSHP injection and extraction of thermal energy is obtained through the medium of rainwater being held in a tanked PPS. The combined system was tested onsite within a prototype sustainable home "The Hanson EcoHouse". This chapter provides a site description; basic information about the EcoHouse; an outline of the approach to the fieldwork; description of the monitoring kits used at the site; an overview of the data collection procedures; and explanations with regard to the large number of observations collected. Towards the end of the chapter the procedure of examining the quality of the harvested water is also presented.

6.1 Site description

The construction of the EcoHouse was completed in the summer of 2007 by Hanson Formpave (part of Heidelberg Cement Group, UK) at the Building Research Establishment (BRE). BRE is a private organization that carries out research, consultancy and testing for the construction and built environment sectors in the United Kingdom. At the heart of the BRE campus is the Innovation Park, which enables the construction industry to showcase the latest innovations in construction. At the start of the current research the EcoHouse was already in place. The prototype house was constructed for the BRE Off-site 2007 Exhibition, and it demonstrated, at the time, the latest developments in off-site masonry construction, thermal mass and natural ventilation.

The Hanson EcoHouse is located, along with seven other eco-constructions, on the Innovation Park at the BRE in Garston near Watford, UK, grid reference 51°42′03″N 0°22′26″ W (Google Earth, 2013), as can be seen in Figure 6-1.

b)

c)

Figure 6-1: The location of BRE at Watford, UK
a & b) Google Maps, 2012; c) Google Earth, 2012

Also, an extension to the Innovation Park with three more eco-buildings was under construction a few months after this research started. The layout of the Innovation Park, presenting the distribution of the eco-buildings can be seen in Figure 6-2. The area surrounding the Innovation Park has office buildings, workshops, a canteen, roads and car parks.

1. Willmott Dixon Healthcare Campus (previously was a school building)
2. The EcoHouse (Hanson EcoHouse)
3. Barratt Green House
4. Stewart Milne Sigma Home
5. Visitors' Centre
6. EcoTech Organics House
7. Osborne House
8. Kingspan Lighthouse
9. Cub House
10. Renewable House
11. Natural House

The extension of the Innovation Park

Figure 6-2: An aerial plan of the BRE Innovation Park

(Source: Insite09, 2011)

6.2 The EcoHouse

The EcoHouse is designed as a detached two-storey, three-bedroom, fully-furnished dwelling. The layout of the EcoHouse is depicted in Plate 6-1.

Plate 6-1: An illustration of the EcoHouse
(Source: Low Energy House, 2011)

The total internal floor area of the EcoHouse is 143m^2 and it is constructed "upside down", with three bedrooms and two bathrooms downstairs, and a large open plan space on the upper floor where the kitchen, dining and living areas are located, as can be seen in Figure 6-3.

Figure 6-3: Layout of the lower and the upper floors of the EcoHouse
(Not to scale)
(Source: Rogatzki, 2010)

The steeply pitched roof is made of zinc and has space for a sky-light, and the central chimney provides natural ventilation (see Plate 6-1). The house was constructed using prefabricated components including precast concrete flooring systems and prefabricated masonry cavity walls 2.4 x 9m, together with traditional building materials (clay block work and concrete brickwork) to form an average-sized family home. The wall panels included openings in which the high-performance doors and windows with three-layered, argon gas-filled glazing would be fitted. The staircase is pre-cast concrete; the ground floor is constructed using Jetfloor® beam and insulation composite block system, whilst the first floor incorporates pre-stressed hollow core floor units.

The key properties of the finished walls include higher flexural strength for both brick and block, increased vertical strength since the wall's strength was about twice that of traditional masonry, and increased resistance to rain penetration of the outer leaf due to the continuous consistent mortar joining. The thin fully-adhered joints also contribute to an air-tightness which is superior to that achieved with traditional masonry. The rate of heat loss through a material is known as its U-value; the lower the U-value, the better the insulation provided by the material. The walls of the house achieved a U-value of 0.18 W/m^{2}K, with a U-value of between 0.15 and 0.27 W/m^{2}K for external walls sufficient to meet Energy Service Directive No. 2006/32/EC. This states that EU countries must achieve a 9% annual energy saving over a period of nine years (2008-2016) through employing new energy services and other energy efficiency measures (INFORSE, 2010). The U-value for the insulated steel framed pyramidal roof was 0.15 to 0.18 W/m^{2}K, and was 0.8 W/m^{2}K for the triple glazed windows. The total heat loss of the constructed EcoHouse was 6.6 kWh/m^2/year (fabric heat loss was 77.9 W/K and the ventilation heat loss was 62.12 W/K) (Hanson customer services, personal communication, 2013).

The architecture company that designed the EcoHouse was TP Bennett, London and its basic shape was inspired by that of a traditional brick kiln, which evolved to take advantage of the principle that hot air naturally rises. A ventilating roof lantern is used to give light and to enhance the natural air currents, thus maximizing the energy conservation potential. The ventilating roof light automatically operates to open and close, depending on the prevailing weather patterns, and so helps to regulate the internal air temperature. However, the ventilating roof was disconnected for the purpose of the study, the reasons for which will be explained later in section 6.3.1.

Additionally, the EcoHouse has high thermal mass creating a structure that can cope efficiently with temperature changes between summer and winter. This inherent feature enables the dwelling to store heat in winter and remain cooler in summer for longer than structures which do not possess high thermal mass. The density of the construction material is exploited to absorb the heat. This heat is then slowly released during cooler conditions, mitigating the effects of temperature change and keeping buildings comfortably habitable in an energy-efficient environment. Also, the constructed envelope took advantage of all the benefits of the masonry panels being manufactured off-site in a controlled factory environment, which, when considered together with the thermal mass and natural ventilation properties, illustrates how quickly and easily high-standard properties can now be constructed.

The landscaping around the EcoHouse is typical of a private housing scheme and includes a surrounding lawn and paved areas and has nearby road infrastructure on the west side. Additionally, there are SuDS techniques (a swale and two water butts) incorporated at the site along with a PPS, which is considered in this study as the main source of water for secondary usage in the EcoHouse (the water collected in the swale is the site rainwater runoff and, if any, the PPS overflow; the rainwater collected in the butts was from the Visitors' Centre and the EcoTech Organics House roofs). The heating and cooling system was based on a GSHP combined with a PPS (there are two PPSs at the site - this will be elaborated on in section 6.2.2); a layout of the elements linked to this study is shown in Figure 6-4. The two systems (PPS and PPS/GSHP) will be explained further in the following sections. To avoid terminology confusions, 'PPS' is the acronym used to denote the Permeable Pavement System and/or the Tanked Permeable Pavement system; 'PPS/GSHP' refers to the PPS merged with GSHP by installing a heat exchanger pipe at the bottom of the PPS to form the combined system.

Figure 6-4: Aerial view of the Innovation Park showing the monitored elements (Source: Insite09, 2011)

In June 2007 the EcoHouse underwent a Code of Sustainable Homes (CSH) assessment. Applying the construction details presented above, together with installing the GSHP and PPS combined system resulted in a highly sustainable and affordable house, which achieved Level 4 under the CSH at that time (see Table 6-2). The PPS gained four credits for surface water drainage and flood risk and five credits for internal and external water usage. The GSHP gained 18 credits in the energy and CO_2 categories. The total number of credits for each category of the CSH, the weighting factors, which reflect the relative importance of each category, and the points achieved by the EcoHouse in each category are presented in the table below:

Table 6-1: CHS categories, credits available for each category, the weighting of each category as a percentage, and points achieved by the EcoHouse (adapted from CLG, 2010a and Hanson, n.d. (b))

Environment impact categories	Credits available in each category	Environmental Weighting Factor (as % of total possible points score available)	Points achieved by the EcoHouse
1. Energy and CO_2	29	36.4%	18
2. Health and Well-being	12	9%	8
3. Ecology	9	7.2%	7
4. Management	9	2.2%	7
5. Water	6	6.4%	5
6. Materials	24	2.8%	6
7. Waste	7	14%	7
8. Pollution	4	10%	1
9. Surface water run-off	4	12%	4
Total	**104**	**100%**	**63**

The relationship between the code levels and total points scored is presented in Table 6-2. The code levels are expressed in terms of a star rating, with the score achieved in each category leading to a final total of points as shown below. One star is the entry level and six stars represent the highest level possible:

Table 6-2: Scores taken from CSH assessment and the ratings derived (adapted from the CSH technical guide, 2007)

Code Levels	Total Points Score
Level 1 (*)	≤36 Points
Level 2 (**)	37 - 48 Points
Level 3 (***)	49 - 57 Points
Level 4 (****)	58 - 68 Points
EcoHouse	63 Points
Level 5 (*****)	69 - 84 Points
Level 6 (******)	85 - 90 Points

In the next section, details of the PPS located at the site are given.

6.2.1 The PPS

The 40m^2 PPS is located around the northern and western sides of the EcoHouse (as seen in Figure 6-4). Underneath the surface of the pavement, there were three different layers; the thickness of each layer in the system was based on the PPS field specifications (Hanson, 2010: 66). However, the depth of the sub-base was extended to 370mm in order to have a greater volume for water storage; the total depth of the PPS is 500mm.

At the bottom of a 500mm excavation, a welded joint impermeable membrane, known as "source control (SC) membrane" (Hanson, 2010: 61; Greenspec®, 2010), was laid on the base and around the sides of the excavation to create a water-tight 'reservoir'. After excavation and prior to laying the membrane, compaction with a vibrating plate was carried out on the soil to give a stable sub-grade. The composition of the layers comprised 370mm of sub-base; the 2mm thick geotextile membrane; a 50mm depth of 2-6mm single-sized crushed clean stone laid on the geotextile; and finally permeable blocks at the top of the system (see Figure 6-5). The gaps between the individual blocks were filled with clean single-sized 3mm pea gravel, which would act as a sealing material. The varying layers of standard pavement aggregates were in accordance with the British Standards requirement (BS EN 13242:2002- guidance on aggregate test methods); aggregates passing this particular standard are suitable as hydraulically-bound materials in civil engineering construction projects and road construction.

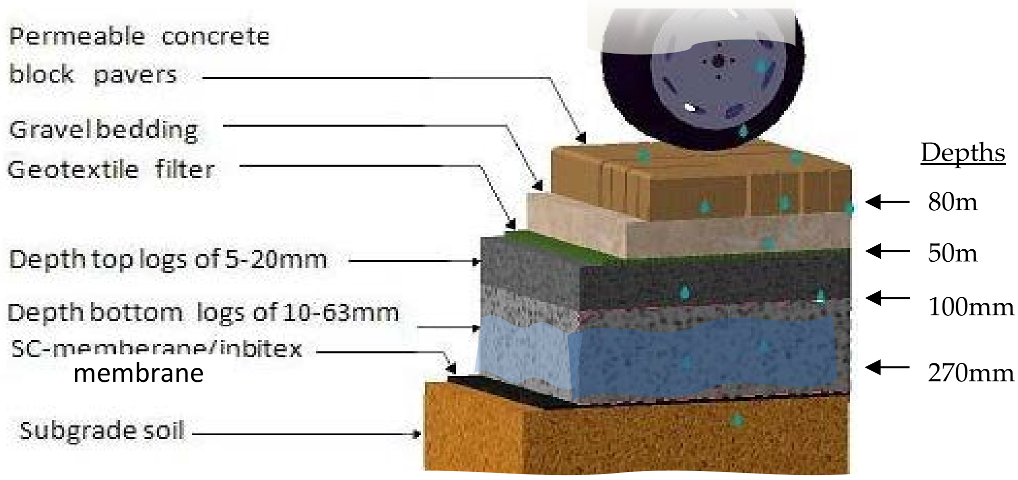

Figure 6-5: A cross-section of a PPS structure
(Not to scale)

(Source: the concept was taken from 'buildinggreen' website and was modified by the author)

The PPS collects rainwater falling on the pavement surface and also the runoff discharged from the EcoHouse rooftop. In the case of the PPS becoming full, excess rainwater would drain to the swale located in the middle of the Innovation Park. The rainwater infiltrated through the vertical channels between the concrete blocks at a rate of 9000 litres/m^2/hour into the sub-base. However, the geotextile layer (which was, specifically, Inbitex geotextile, as explained further in this section) beneath the laying course will allow approximately 4500 litres/m^2/hour through and this figure should be taken into consideration for design purposes (Hanson, 2010: 12).

The PPS contained an electric pump located in an internal concrete sump in the sub-base (Plate 6-2) in order to transfer the collected rainwater into the house for flushing the two WCs, and to provide for external uses such as car washing and irrigating the garden; these uses may reduce by up to 50% the household requirements for mains water (Hanson, 2010: 20). The pump also allowed the harvested rainwater to be dispensed via a tap and hose-pipe.

Plate 6-2: An internal concrete sump
(Picture captured at BRE, 2009)

The Permeable Blocks: permeable blocks are described by Formpave Ltd. as a 'storm water source control system' (Hanson, 2012). The blocks at the surface of the PPS used at the EcoHouse, supplied by Formpave Ltd., were 100 x 200 x 80mm. Figure 6-6 illustrates the PP blocks (dimensions are in millimetres).

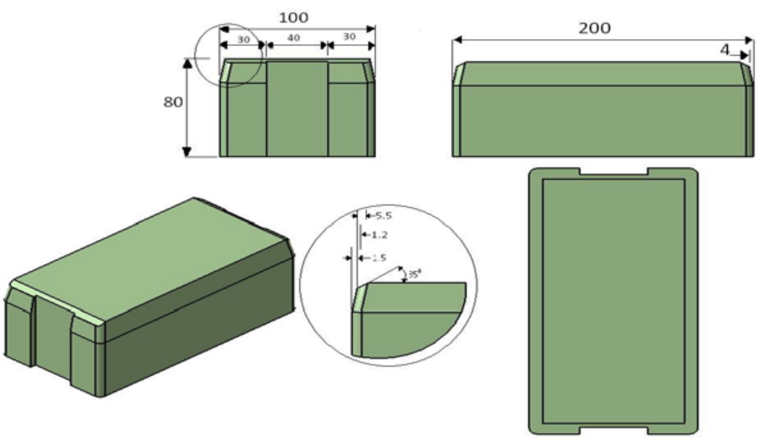

Figure 6-6: Permeable blocks

(Not to scale)

The Geotextile: geotextile is manufactured from polypropylene and polyethylene, the specific type used in this system being 'simple' Inbitex. It was placed in the top part of the upper base. Infiltration is achieved by non-woven geotextile specifically developed to optimise the cleansing of water entering the system, and to perform better than woven textile in terms of filtering, retaining pollution and separating products (Newman *et al.*, 2006).

The Sub-base: The material used for the sub-base was crushed stone free from sharp protrusions likely to puncture the membrane, made in accordance with the resistance to fragmentations-Los Angeles coefficient (which is a test of the strength of the aggregate and how easily it breaks apart). The sub-base was made up of two layers; the upper sub-base layer was 100mm thick and comprised aggregate of 5-20mm diameter, while the lower part of the sub-base was 270mm thick and comprised a 10-63mm stone. The compacted sub-base had a voids ratio of approximately 30%. A fully welded SC membrane was placed at the bottom of the sub-base and lapped over both sides to prevent water from infiltrating into the surrounding soil and therefore providing a water-tight system. This structure adds tensile resistance, and also prevents sub-grade deformation. The SC membrane together with the voids of the sub-base allowed storm water to be attenuated in the system and released in a controlled manner over a period of time. The structural integrity of the paving blocks and the sub-base design were suited to light duty only; in other words they could not cope with heavy loading - but they constituted the kind of structure which would be found in use in the typical private driveway of a house.

The area of the PPS was insufficient for producing enough energy for the heating and cooling of the EcoHouse, and so the GSHP/PPS combined system was installed at a different location in order to have enough space to enable it to work satisfactorily; this will be explained in detail in the following section.

6.2.2 The GSHP

At the EcoHouse, the main three components of the GSHP (described in the previous chapter, section 5.1) are located as follows: the heat pump and the thermal distribution system are located indoors; and the coil is outdoors, immersed in the PPS/GSHP system, and located 30m away from the PPS to the east as shown in Figure 6-4.

From the structural point of view the two PPSs (one on its own, the other combined with the GSHP) are similar; however, there were some difference in the design. The similarities and differences are shown in Table 6-3:

Table 6-3: The structural differences between the PPS and the PPS/GSHP

	PPS	PPS/GSHP
Area	40m^2	65m^2
Permeable blocks	80mm	80mm
Clean stone (2-6mm)	50mm	50mm
Geotextile	Inbitex	Inbitex composite
Coil	×	✓
Sub-base	Upper layer 100mm (stone size 5-20mm)	Upper layer 120mm (stone size 5-63mm)
	Lower layer 270mm (stone size 10-63mm)	Lower layer 100mm (6mm pipe bedding stone)
Total excavated depth	~ 500mm	~ 350mm

Usually, it is recommended to bury the horizontal ground heat exchanger (GHE) in shallow trenches of around 1m depth (Energy Saving Trust, 2004). However, the literature does describe the application of a horizontal GSHP where the GHE was buried at a depth of 500mm (0.5m) (Singh *et al.*, 2010). The GHE at the current site is laid at a depth of 350mm (0.35m). This depth is less than the minimum design for horizontal shallow trenches. The reason for this originates from the installation phase, when a large concrete slab was found on excavating at around 350mm, and which proved very difficult and complicated to break through. The excavation had to stop therefore at this depth of 350mm instead of the 500mm planned originally. However, to ensure that the coil was covered with enough rainwater for appropriate heat fluxes and heat exchange through the system, it was agreed with the constructors of the adjoining buildings during the construction stage of the EcoHouse for the PPS/GSHP to receive discharge rainwater from the roofs of the adjoining buildings so as to maximise the volume of collected rainwater. Up to 6 KW of heating or cooling energy can be produced from the 65 m^2 PPS installed at BRE, and potentially this is more than enough power to maintain a comfortable year round temperature inside the dwelling space (Geothermal International Ltd., 2007).

The differences in the sub-base design for the two reservoirs (PPS and PPS/GSHP) shown in Table 6-3 were a result of limiting the excavation depth for the PPS/GSHP to 350 mm instead of 500mm, as explained above. The thickness of the sub-base layers at the PPS/GSHP, however, was different since it was shallower, but also because the sub-base arrangements were different. This was mainly because a layer of 100mm deep of 6mm bedding stone should, according to PPS design criteria (Hanson, 2010), be laid at the bottom of the reservoir in order to protect the impermeable member from any damage during the process of installing the GHE. Subsequently, a depth of around 120mm was remaining from the excavation for the upper layer. Therefore, a crushed stone size 5-63mm (the stones of different sizes designed for the upper (5-20 mm) and lower (10-63 mm) layers were merged) was used to fill up the upper sub-base. Although such a shallow sub-base may affect the storage capacity (as explained in section 3.1), the Formpave engineers and the construction team at that time found it acceptable mainly because of the arrangement of receiving discharge rainwater from the roofs of the adjoining buildings (mentioned above) to compensate with the GSHP/PPS sub-base adapted set-up. Figure 6-7 illustrates the layout of the PPS and PPS/GSHP installed at the site (dimensions are in millimetres):

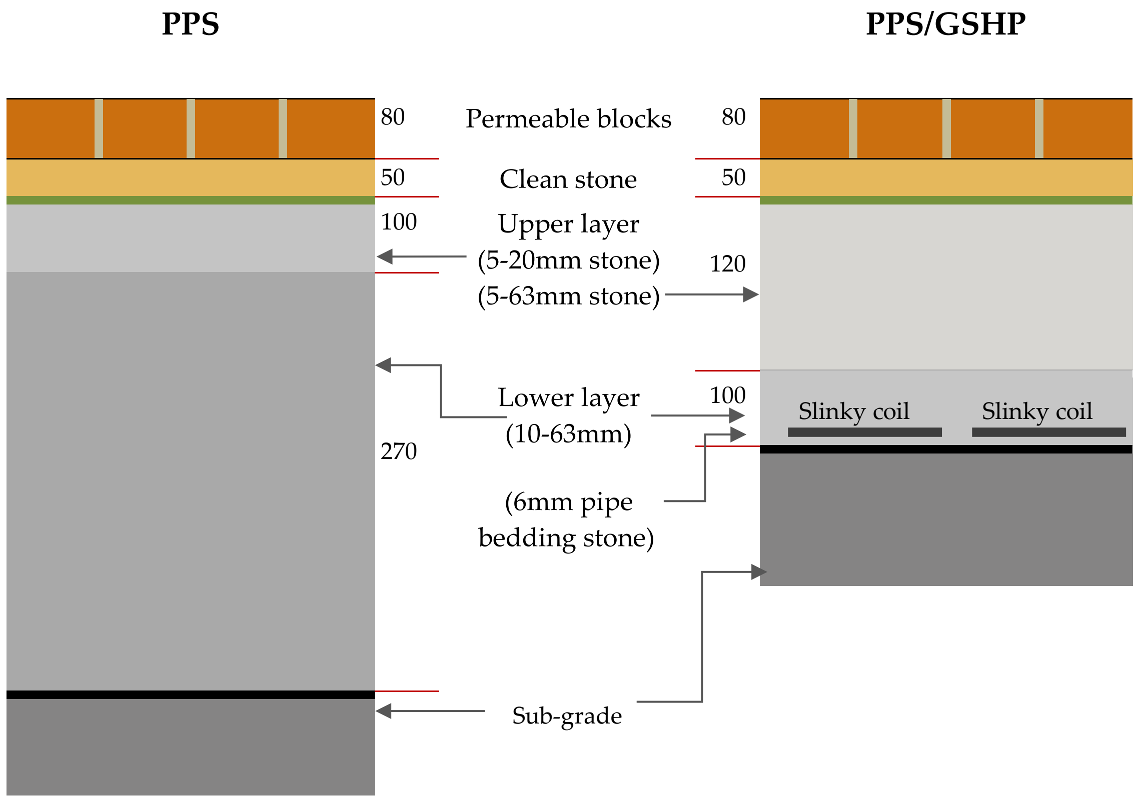

Figure 6-7: A schematic layout of the PPS and the PPS/GSHP

The type of geotextile which was utilised in the PPS/GSHP was Inbitex™ composite, which is Inbitex™ laid together with an impermeable layer (Grabowiecki *et al.*, 2008), and is illustrated in Plate 6-3. The impermeable layers overlapped each other so runoff rainwater could penetrate the geotextile and percolate through the system while at the same time avoiding evaporation (Gomez-Ullate *et al.*, 2010).

Plate 6-3: Inbitex™ composite (Picture captured at BRE, 2008)

The heat exchanger used was of the slinky pipes type, 50mm in diameter and 150m long, set horizontally in the sub-base of the PPS (see Figure 6-8), and linked to the heat pump with anti-freeze circulated through the coil pipes to extract the geothermal energy. Such a slinky loop arrangement is space-efficient, suitable for dwellings with limited open space in which to lay the ground loop (Singh *et al.*, 2010). A protective fleece was put over the excavated area to prevent puncturing of the SC membrane.

Figure 6-8: Tanked PPS including a heating/cooling element
(Source: Hanson, n.d.(a) – modified)

The heat pump was located inside the EcoHouse on the lower floor (location shown in Figure 6-3), and powered by electricity; however, the use of electricity is mitigated by a performance coefficient of 4:1. The specifications of the heat pump's components are as follows:

Table 6-4: Specifications of the heat pump

Manufacturer	Water Furnace Company
The performance standard	AHRI/ASHRAE/ISO 13256-2
Type	The Envision Series – NDW unit
Capacity	8KW
Antifreeze	Ethylene Glycol

The heat distribution system is an indoor unit. The heat is transferred via under-floor piping which is used as a heat distribution system.

6.3 Approach to PPS/GSHP monitoring

The main aim of the research was to answer the question of whether the PPS/GSHP was capable of providing the domestic setting with a comfortable temperature all year round. Also of interest would be whether absorbing heat (in the heating mode in winter) would have a long-term effect on the temperature of the ground surrounding the coil; whether the GHE pipe would remain immersed in stored rainwater throughout the monitoring period; and whether the system could still provide heat efficiently even if the heat source (the rainwater) temperature dropped to below 0°C. To obtain answers for these questions, the following elements have been monitored throughout the study:

- The EcoHouse itself, specifically the temperature of the exterior and interior walls.
- The ground temperature at varying depths below the surface of the pavement of the PPS/GSHP.
- The rainwater level in the reservoir.
- The air temperature above the surface of the PPS/GSHP pavement.

6.3.1 Measuring the temperature of the habitable spaces of the EcoHouse

To monitor the temperature inside and outside the house, nine constantan (copper/nickel alloy) thermistor sensors were embedded in the external and the internal panels. The EcoHouse was constructed with prefabricated brick and block cavity external wall panels comprising 102mm clay facing brickwork outer leaf, and a partial fill cavity of 100mm Kingspan® rigid insulation with a 50mm air space. The overall width of the walls including plaster finish was 365mm. The temperatures were measured through sensors embedded in the internal and external panels separately (Figure 6-9), on the four sides of the EcoHouse, North, South, East and West, as illustrated in Plate 6-4, along with a partition wall at the lower floor inside the EcoHouse (between room 2 and room 3, shown in Figure 6-3).

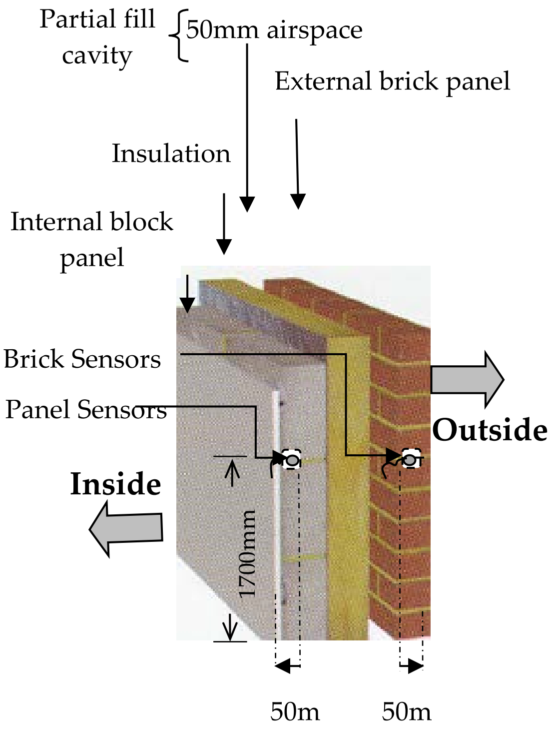

Figure 6-9: Section of the wall a the EcoHouse including the sensors

The sensors were buried 50mm deep in the panels in order to demonstrate the impact of GSH capture/exchange on the temperature inside the house compared with that outside, and whether the inside temperature would be comfortable for the users or inhabitants. They were connected to a Tridium

Java Application Control Engine (JACE) 200 logger system. The measured data were sent to the data-logger via an ultra-high bandwidth fibre connection to a Community Digital Management Centre based in the Visitors Centre. The data were then downloaded to a PC in DOS format. The whole system was controlled by a computer and operated automatically. This package of the automating technology and the in-home wiring, together with coordinating the installation and integration of equipment and services from a range of suppliers was arranged by OpenHub Limited, and the temperature data were sent to the author in a Comma Separated Variable (CSV) format. The heat pump was adjusted by the supplier so that when in cooling mode the system prevented the temperature decreasing by more than 5°C and the thermostats prevented the heater from providing heat beyond 29°C by switching the system off; these figures were relatively similar to Scholz and Grabowiecki's (2009) temperature adjustments. The pump system at the EcoHouse works continuously to provide heating to the house during the entire year, and a constant temperature of 20°C was set on the heat pump. Additionally, the control panels at each room inside the EcoHouse were adjusted for the same temperature as indicated on the heat pump.

The performance of GSHP in the present study was investigated only in heating mode; technical difficulties (e.g. problems switching the control panel of the pump from heating to cooling mode) prevented it being used for cooling the house. Recording the temperature readings started on 12th March 2008 and carried on up to 21st November 2010 (i.e. 32 months and 9 days = 985 days). To maintain constant monitoring, temperature readings were recorded periodically with a 34970A Agilent data acquisition system set at 10-minute intervals. The reason for choosing an interval of ten minutes was to cover the temperatures of the house during the day as much as possible, and to minimise the effects of spurious temperature readings due to visitors entering and leaving the house, raising the possibility of outdoor air entering the house, and resulting in 'false' temperatures being recorded for the habitable spaces. Additionally, the roof ventilation (shown in Plate 6-4) was disconnected during the monitoring period, since by keeping the roof closed the warm air (heat) provided by the GSHP could not escape and the cold outside-air could not enter the house and affect the temperature readings.

Plate 6-4: A schematic of the EcoHouse showing the North, East, West and South walls

(Source: offsite2007, 2009)

6.3.2 Measuring the PPS/GSHP characteristics

Two parameters inside the constructed reservoir were measured, as shown in 6.3.2.1 and 6.3.2.2:

6.3.2.1 PPS/GSHP ground temperatures

As it was compatible with the structure of the PPS/GSHP system, the ground temperatures under the paving surface were obtained by placing four thermal electrodes (sensors) in the sub-base at various depths, as can be seen in the experimental set-up depicted in Figure 6-10 and in Plate 6-5 (a & b), in order to investigate the ground heat distribution, and the characteristics of the heat transfer from the ground to the heat exchanger; in other words, to understand the primary heating processes of the PPS/GSHP. The distribution of the sensors was planned to give a whole picture of the temperature of the ground at the time heating was provided to the building.

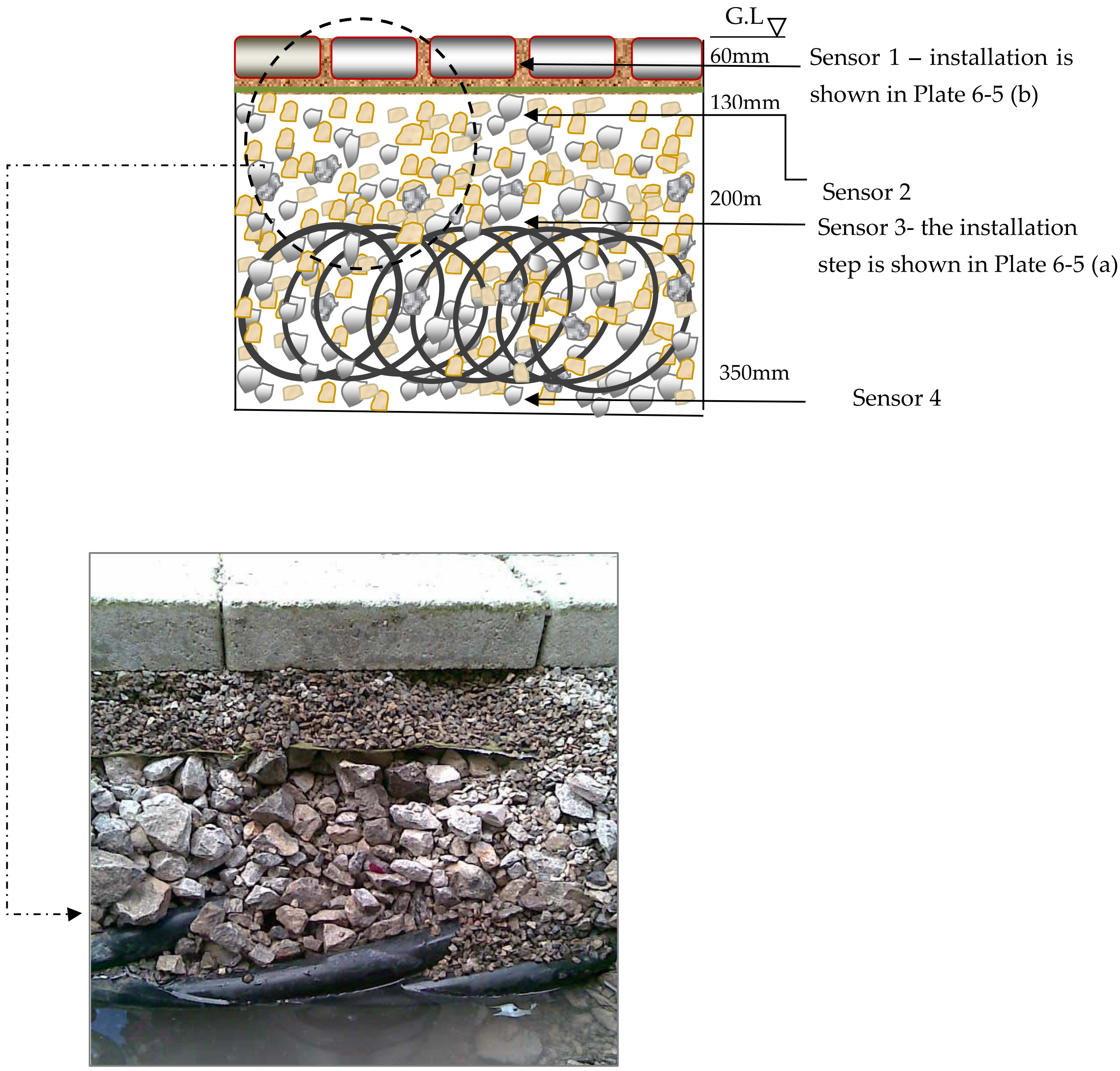

Figure 6-10: a) A sketch of the positions (locations) of the sensors buried in the sub-base (Not to scale); b) PPS/GSHP at BRE

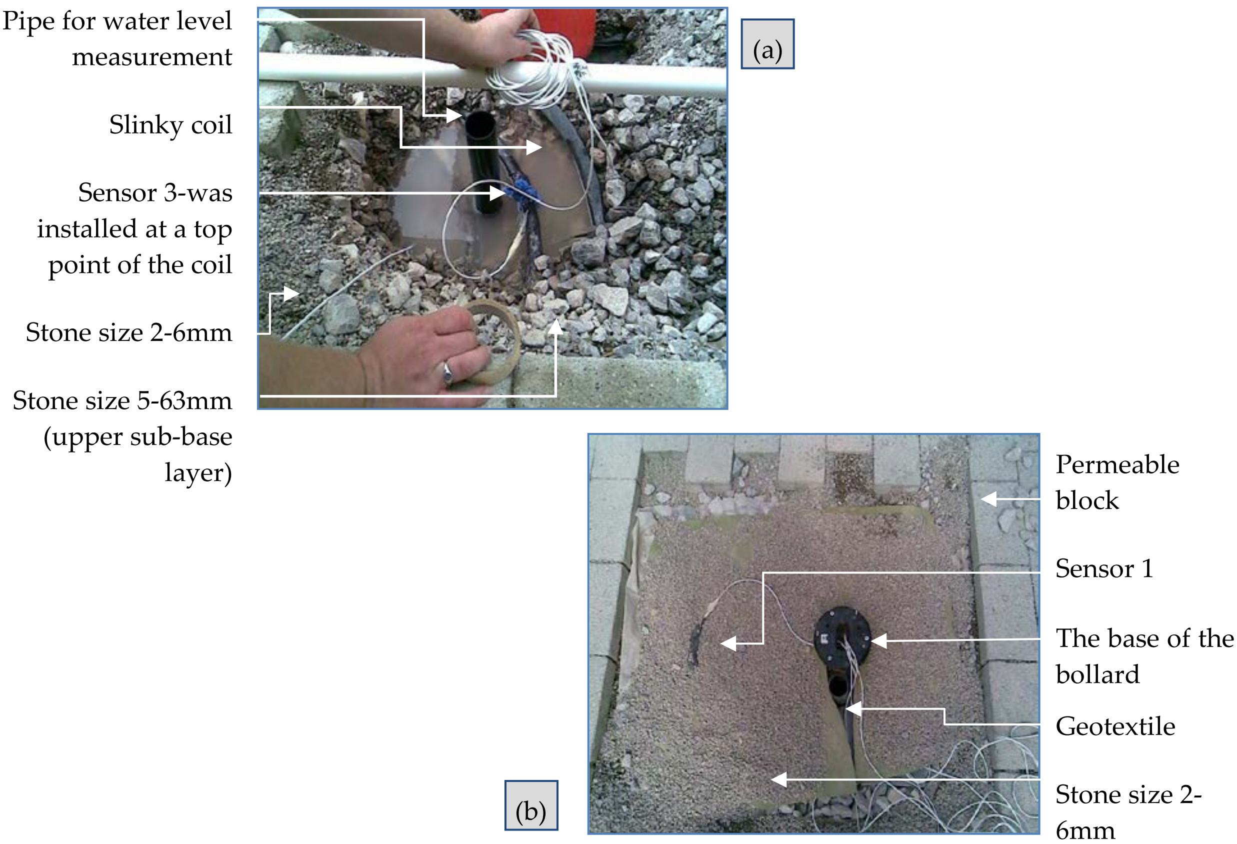

Plate 6-5: Steps of placing the thermal electrodes in the PPS/GSHP system

(a): Shows sensor 3 attached to a top point of the exchanger pipe

(b): Shows sensor 1 ready to be placed between two paving block

The ground temperature and the overlying air temperature (explained in section 6.3.3) were, for purposes of uniformity, measured and recorded periodically in the same manner as those for the space inside the house, that is to say readings from these locations were continually recorded at 10-minute intervals. However, the ground and air monitoring pieces of equipment were installed on 8th August 2008 (a few months after installing the sensors in the walls at the EcoHouse) and readings were taken up to 30th March, 2010 (i.e. 19

months and 22 days = 600 days), resulting in unequal measuring periods. The measured data were transferred to a data logger and stored on a PC.

Apart from monitoring ground temperature of the PPS/GSHP, the other concern was monitoring the height of the rainwater stored in the PPS/GSHP, since the fundamental concept of this combined system is based on keeping the heat exchanger pipes immersed in the harvested rainwater.

6.3.2.2. Measuring PPS/GSHP water level

One of the key aspects of integrating the PPS with GSHP is that the heat extraction pipes are constantly submerged in rainwater so that the local heat in the stored rainwater is replenished by the introduction of geothermal energy from the ground (as explained in the introduction of Chapter Five, section 5). Therefore, a pipe was installed perpendicularly to the top layer of the paving blocks, cutting through all aggregate layers, to the bottom of the PPS/GSHP reservoir. The depth of the stored rainwater in the reservoir was measured using a thin wooden stick in order to monitor whether the stored rainwater was submerging the extraction pipes. During times of severe cold, if the rainwater in the PPS/GSHP froze it was not possible to take water depth measurements. The PPS was also monitored so that the two systems could be compared in terms of the state of the rainwater (frozen or unfrozen).

6.3.3 Measuring the air temperatures

A bollard was installed at the PPS/GSHP (see Plate 6-6) in order to monitor the temperature of the air above the combined system. The bollard contained two sensors, embedded at heights of 1300mm and 50mm from the pavement surface to monitor the air temperature at these points. Temperatures gathered from the higher sensor were taken to represent the ambient air temperature at the site, whilst temperatures were taken from the lower sensor in order to study the influence of the PPS/GSHP system on the air temperature when evaporation could occur near the paving surface and with minimal winds.

Plate 6-6: The air temperature bollard installed above the GSHP tank

The justification for using temperatures taken from the sensor located at 1.3m (1300mm) above the ground is that this is in line with The World Meteorological Organization standards for the height of thermometer for measuring air temperature, namely between 1.25 m (4 ft 1 in) and 2 m (6 ft 7 in) above the ground (WMO, 2006). Placing the lower sensor at 50mm above the surface of the pavement reduced the effect of interference by the wind, enabling constant air temperature measurement to be taken (Arnfield, 2003).

Relative humidity was one of the measurements taken into consideration in the current study; however, the humidity data set was rejected because of doubt in its validity since large variations between the recorded values were found within the short 10-minute intervals. The collected figures for humidity were compared with the meteorological data from a weather services website, namely the 'Weather Underground' website (www.wunderground.co.uk), and a sizeable variation was found; hence they were rejected as outlier, being clearly out of conformity with real measurements.

The temperature readings collected at the site from the three different locations are set out in the following section.

6.4 Dataset

The number of sensors placed at each location for temperature monitoring had an effect on the sum of observations gathered at that particular place. Also, the fact that each of the site locations was monitored for different lengths of time resulted in a different number of observations for each location. Hence, by using the number of sensors at each location and the duration of monitoring, the expected number of temperature observations for each location was calculated (the calculations are presented in the Appendix), and were 1,794,960. However, this number of observations was only the *expected* amount of readings to be collected during the monitoring period; *in reality,* the actual total number of observations was smaller for the following reasons: **1)** power failure during emergency electricity shut down, **2)** system repair events, **3)** temperature readings not being recorded in the data logger for unspecified reasons. Also, in the initial data analysis, some measurements were omitted because they were potentially misleading; for instance there were some days on which only a few temperature readings were recorded, presumably because the data logger was 'flickering' between 'on' and 'off', because of power outages and so forth, as mentioned above. The periods of data logger instability were sometimes a matter of hours, sometimes days and on occasion lasted for more than a week. The temperature readings that were recorded after or during such events were occasionally intermittent, i.e. were not always recorded at 10-minute intervals, and were only recorded for a short time during the day, resulting in temperature readings clustered around certain parts of some days. An example of this was on 8th May 2009, when readings were taken every ten minutes up until 12:45PM; after this, recording of the temperature readings was interrupted and only restarted again on 23rd June 2009. There were only two temperature readings collected on this date; one at 16:31PM and the other reading was at 17:27PM. Thus, the means of readings recorded on such days were not considered to be accurate and so were excluded so that they did not detract from the reliability of the data.

Furthermore, the readings recorded on the 23rd June 2009 (mentioned above) were the only temperature readings that were recorded in that particular month; the next reading recorded was on the 6th July 2009. Such little information for a whole month would be misleading when the monthly average is computed, thus June 2009 readings were omitted. While setting up the data logger to record temperatures at 10-minute intervals was initially considered as being too frequent, possibly yielding too much information, the real benefit of having done so becomes apparent when considering the effect of inconsistencies such as those discussed above. Relatively insignificant amounts of data have been 'lost' thanks to having opted for logging at the short, 10-

minute intervals, and thus the temperatures of the different media (wall surface, ground, and air) recorded at each location can be considered as being accurately reflected.

Thus, the actual sum total of observations collected during the monitoring period was 1,303,379 instead of 1,794,960; and the number of days on which there was data collection, see Table 6-5, were fewer than those mentioned in section 6.3.1 and 6.3.2.1; that is about 72.6% of the number of observations that would have been collected if there had been no data 'missing' for the reasons mentioned above.

Table 6-5: Differences between the potential and actual number of observations

Locations from where the observations were recorded	Potential number of observations*	Actual number of observations	Actual duration (number of days' worth of collected data)
The EcoHouse	1,276,560	902,151	718
The PPS/GSHP reservoir	345,600	255,570	509
The bollard above the reservoir	172,800	145,658	509
Total number of observations	1,794,960	1,303,379	

* Calculations are shown in the Appendix

The *actual* numbers of observations (shown above in Table 6-5) are ultimately the sum of the number of temperature readings collected from sensors installed on site, i.e. 9 sensors at the EcoHouse, 4 sensors at PPS/GSHP reservoir, and 2 sensors above the pavement surface (see Table 6-8), used at each location. This is presented in Table 6-6.

Table 6-6: Number of observations collected by each sensor

Location	Sensors position		No. of observations
EcoHouse	North	Internal	100,239
		External	100,239
	East	Internal	100,239
		External	100,239
	West	Internal	100,239
		External	100,239
	South	Internal	100,239
		External	100,239
	Partition wall		100,239
SUM			**902,151**
PPS/GSHP reservoir	At 60mm below ground surface		72,829
	At 130mm below ground surface		72,829
	At 200mm below ground surface		72,829
	At 350mm below ground surface		37,083
SUM			**255,570**
The bollard standing on the surface of the PPS/GSHP	At 50mm above ground surface		72,829
	At 1300mm above ground surface		72,829
SUM			**145,658**
Total			**1,303,379**

Table 6-7 presents the number of observations recorded on a yearly basis at the three locations that have been monitored during the study.

Table 6-7: Number of observations recorded on a yearly basis at the monitoring locations

Dataset / Year	Wall surface observations	The PPS/GSHP reservoir observations	The bollard observations
2008	280,557	43,195	22,638
2009	344,124	184,682	105,120
2010	277,470	27,693	17,900
Sum for each location	902,151	255,570	145,658
Total number of observations	1,303,379		

It is also worth mentioning that there was no gross outlier observed in the data set. This was confirmed when the validity of the extreme temperature values found in the data set was examined. The lowest temperature in the entire data set gathered at ten minute intervals was one for air temperature recorded from the bollard at a height of 50mm from the surface of the PPS/GSHP; this was -6.3°C recorded on 7th January 2009. This temperature was checked against ambient temperature recordings on the same date from the online meteorological website mentioned previously (www.wunderground.com), weather data for which is recorded at a station based at Northolt, 12Km from BRE's location, and it was ascertained that the temperature on the date in question ranged between -9.0 and 2.0°C. Therefore, the -6.3°C was found acceptable as it falls within this range. The highest recorded temperature in the data set was 54.0°C, found in the EcoHouse external panels data, on the 23rd May 2010. The 54.0°C was not considered as being an outlier even though it might stand out at first sight as 'much too high' because it can in fact be explained as a result of direct sunlight hitting the dark red bricks (used on the outer surface of the EcoHouse building) over a long sunny day (Rosenfeld *et al*., 1995; Masonry Construction Magazine, 2000; Sandifer and Givoni, 2002). It is also important to remember that the sensor was embedded 50mm from the surface of the external wall panel, and so really was measuring the temperature of the surface of the wall rather than that of the air. Relating this high temperature at the external panel to the effect of sunlight was supported by weather history data from the meteorological website (www.wunderground.com), which stated that on the 23rd May 2010 sunrise and sunset were at 4:59AM and 8:58PM, i.e. day-length was 15h 59m, the atmospheric conditions of the day were clear, with visibility throughout almost 50Km, and with the mean temperature between 5:50AM and 8:50PM being 21.9°C, all of which supports the acceptance of this highest recorded degree (54.0°C) as an accurate figure and not an outlier.

The data collected at the site were analysed using descriptive statistics which included measures of central tendency (mainly the mean); measures of variability which included the standard deviation, and minimum and maximum variables; and a further analysis using a t-test. The measures were carried out using Microsoft Excel and SPSS software.

Summary

The potential benefits of integrating the PPS and the GSHP in one combined system were highlighted in the previous chapters. However, in order to fulfil the objectives of this research, the combined system was to be applied at a domestic setting subject to real life conditions. A prototype furnished detached family-sized house, referred to as the EcoHouse, consisting of two floors, with three bedrooms, a kitchen and two toilets located at BRE innovation park, Watford, UK was used to assess the performance of a PPS/GSHP system for heating purposes. The landscape around the domestic setting was typical of a private housing scheme including surrounding lawn, pavement and nearby road infrastructure; a swale and two water butts were also incorporated at the site.

In this chapter, the layout of the site where the EcoHouse and a number of other eco-buildings are built was illustrated and the EcoHouse, which is a code four building envelope, was described. A PPS and a PPS/GSHP were applied at the site for the benefit of the domestic setting. The PPS was the source of water for secondary usage, and the PPS/GSHP was used for heating purposes. The structural designs for the two systems were demonstrated in section 6.2.2.

While excavating for the PPS/GSHP reservoir installation, a large concrete slab was encountered, which resulted in limiting the excavation at a depth of 350mm. To overcome this problem, a decision was made at the time with the constructors of the adjoining buildings during the constructing stage of the EcoHouse for the PPS/GSHP to receive discharge rainwater from the roofs of the adjoining buildings, so as to maximise the volume of collected rainwater in the underground reservoir to ensure that the coil was always covered with

enough rainwater for appropriate heat fluxes and heat exchange to occur in the system.

Furthermore, the monitoring kits used during the study were installed for the purpose of taking temperatures readings from different locations at the site; they were all presented in this chapter showing the types, positions, and the settings of each kit. The number of sensors used at the site and a description of their positions are summarised in Table 6-8:

Table 6-8: Number of sensors used for monitoring and their locations

Location	Description	No. of sensors
EcoHouse	The sensors were installed indoors and outdoors to measure the temperature of the external and internal surfaces of the panels on the four sides of the house (North, South, East and West) and on an internal partition wall.	(4 wall panels x 2 sensors on each wall) + a sensor on the partition internal wall **= 9 sensors** (see section 6.3.1)
PPS/GSHP reservoir	The ground temperature under the paving surface were obtained by placing the sensors in the sub-base at four different depths	**4 sensors** (see section 6.3.2.1)
The bollard standing on the surface of the PPS/GSHP	The bollard contained two sensors installed at different heights to record air temperatures above the surface of the combined system	**2 sensors** (see section 6.3.3)
	Total	**15 sensors**

The sensors were connected to a data logger on which the temperature readings were recorded every ten minutes and sent then to a PC. The monitoring kits were installed at different points in time; consequently, the temperatures at each location were measured across different durations, which resulted in different amounts of data collected at each location. The total number of observations collected between 12th March 2008 and 21st November 2010 was 1,376,208. The collected data is analysed in Chapters Seven and Eight, and discussed in Chapter Nine. However, the periods of collecting temperature readings from the monitored locations are summarised below in Table 6-9.

Table 6-9: Periods of monitoring each location at the site of research

Location	From	To	Duration (months, days)
EcoHouse	12th March 08	21st Nov. 10	32m, 9d (985 days)
The PPS/GSHP reservoir	8th August 08	30th March 10	19m, 22d (600 days)
The bollard above the PPS/GSHP	8th August 08	30th March 10	19m, 22d (600 days)

Furthermore, a number of issues that frequently affect field studies of this type were explained, specifically the problems that occurred during the installation of the PPS/GSHP. Some solutions for overcoming these problems were also explained in this chapter, in section 6.2.2.

In the next chapter, the data collected from the site during the monitored period are processed and analysed.

Chapter 7 : Analysis of temperature data collected at the site

Introduction:

In Chapter Six, the EcoHouse, the PPS/GSHP reservoir set-up and the monitoring bollard were described, and the locations of the sensors with explanations for the numbers of temperature readings collected were presented. In this chapter, the EcoHouse indoor temperature data is analysed in a number of steps: an 'all years' period, then yearly sub-periods, and finally, in monthly sub-periods, in order to carefully study the thermal characteristics of the envelope. The monitored exterior temperature was used as an indicator of whether the temperatures were low enough so as to require heating of the habitable or 'dwelling' space over the examined period, and also for comparison purposes. The thermal characteristics for both the air temperatures collected from the bollard and for the ground at four different depths are presented.

7.1 Data Analysis

The temperature data sets gathered during the monitoring period were taken in winter, spring, summer and autumn at 10-minute intervals over almost three years, providing much data for analysis. Manipulating such a large amount of information was a significant part of this research, since interpreting the quantity of readings yielded would not be feasible at a glance; the data sets needed to be processed and organized logically and systematically. Although numerous research projects have been carried out previously in which temperature data were similarly collected by using embedded sensors connected to a data logger, for example Michopoulos *et al*. 2007; Florides *et al*., 2011; Esen and Inalli, 2009; Boait *et al*., 2011; and Jalaluddin *et al*., 2011, these did not provide any detailed information on how to deal with the massive number of gathered data readings. The large amount of quantitative data obtained during the monitoring was manipulated in a series of steps to produce a more manageable data set, and explanations surrounding this are given in this chapter.

The data sets were classified into three sub-sets according to the location they were collected from: **a)** The EcoHouse, **b)** PPS/GSHP reservoir, and **c)** The bollard located above the PPS/GSHP. Since the temperature data for each location were collected at 10-minute intervals, charting all the recorded observations would not be possible with standard statistical packages such as Microsoft Excel. A useful approach of summarising the observations was to work out descriptive statistics by measures of central tendency within a sample (Sullivan, 1967). Since the ‘average’ is a statistical description and is a particularly informative measure of the "central tendency" of a data sample, the 10-minute intervals temperature readings were averaged to form a single, representative ‘day’; this was applied assuming that the average would represent a value accounting for an overall temperature distribution, which could be used for plotting the temperature pattern. This could be calculated easily, since the logger recorded the time and date of all measurements.

The results of analysing the EcoHouse indoor temperature readings are presented in section 7.1.2 of this chapter. Nonetheless, in order to demonstrate confidence and variability in the data collected, the levels of variation between the four walls and the differences between the inner and the outer walls are given in the following section.

7.1.1 Variability in the data collected

The temperature readings were collected from the north, south, east and west sides of the EcoHouse, from the inside and the outside walls of the envelope, as explained previously in section 6.3.1. In order to measure variation of all values from the mean for each wall (inside and outside), standard deviation was computed. The values of the standard deviation for inside walls was around 4°C, whilst it was up to 7°C for outside walls; i.e. there was more variability in the temperature readings for the outside walls than for the inside. This may be due to fluctuation in the outside temperature as it is more exposed to the prevailing weather conditions. For further demonstration, the difference between the four walls and the difference between the inside and outside walls are presented in Figure 7-1, and their statistical analysis summarized in Table 7-1.

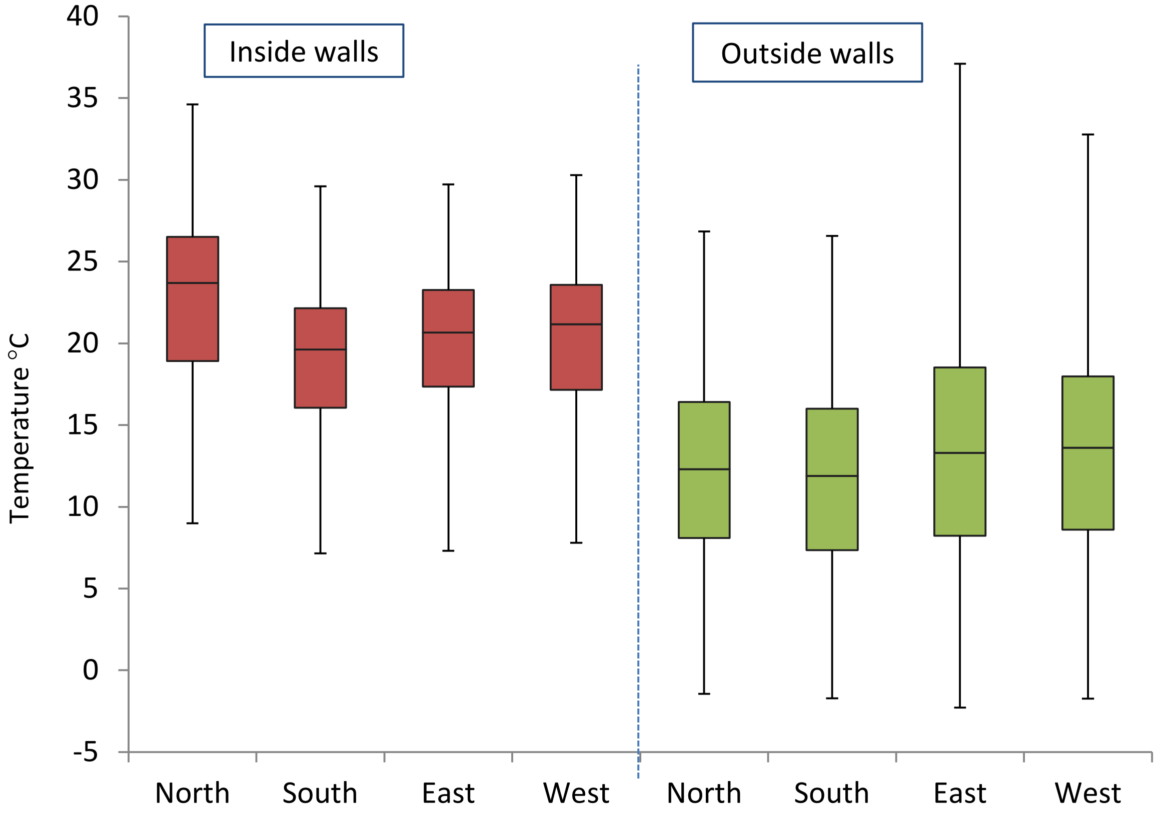

Figure 7-1: The difference between the north, south, east and west inner and outer walls (n = 5,744)

Figure 7-1 shows clearly that, during the monitoring period, the inside walls recorded higher temperatures in comparison with the outside walls (the statistical analysis for each individual wall (inside and outside) are given in Table 7-2). On average, the inner walls were 8°C warmer than the outer walls. The main characteristics and the differences between the inner and outer walls are summarized in the following table.

Table 7-1: The temperature difference between the inner and outer walls

	Inner walls (°C)	Outer walls (°C)	Difference (°C)
Minimum	7.1	-2.3	9.4
Maximum	34.6	37.1	2.5
Range	7.1 (min)	37.1 (max)	30
Average	20.5	12.5	8

Furthermore, measures of variability for data collected from each wall (inside and outside) are presented in Table 7-2. The table shows that the north inside wall registered the highest mean temperature in comparison with the other inside walls, the west outside wall recorded the highest mean temperature for the outside walls, followed by the east outside wall (with only 0.2°C difference). This can be attributed to the orientation of the sun; the east side gets morning light during sunrise, whilst the west side receives sunlight during the after-noon and at sunset. Subsequently, sunlight penetrating the glazed windows and glazed doors on the east and west sides of the EcoHouse was partially hitting the inside north wall causing its temperature to increase more that the inside walls on the other sides of the building (partition walls stopped sunlight coming from the east side to fall on the west inside wall and vice versa). The sun orientation is also the explanation for having the east and west outside walls warmer than the north and south outside walls. Nonetheless, although the sun travels across the southern sky between the period of sunrise and sunset, in the case of the BRE EcoHouse, the Willmott Dixon Healthcare Campus (see Figure 6-2), was constructed on the south side of the EcoHouse, and obstructed the sun from hitting the outside south

Table 7-2: Variability of temperature data collected from the inside and outside walls of the EcoHouse

EcoHouse Walls		n	Mean	Stdev	Std. error	Variance	Median	Min	Max	Range	Q1	Q3	Interquartile range
North	Inside	718	22.7	4.96	0.19	24.65	23.7	9.0	34.6	25.6	18.91	26.52	7.62
	Outside	718	12.0	5.67	0.21	32.14	12.3	-1.4	26.9	28.3	8.09	16.41	8.32
South	Inside	718	19.1	4.10	0.15	16.88	19.6	7.1	29.6	22.5	16.05	22.15	6.09
	Outside	718	11.4	5.87	0.22	34.45	11.9	-1.7	26.6	28.3	7.35	16.01	8.66
East	Inside	718	20.1	4.25	0.16	18.05	20.7	7.3	29.7	22.4	17.35	23.27	5.92
	Outside	718	13.2	7.02	0.26	49.25	13.3	-2.3	37.1	39.4	8.22	18.54	10.31
West	Inside	718	20.3	4.24	0.16	17.95	21.2	7.8	30.3	22.5	17.15	23.57	6.42
	Outside	718	13.4	6.52	0.24	42.56	13.6	-1.7	32.8	34.5	8.61	17.97	9.36

n: number of observations; **Stdev**: standard deviation; **Std. error**: Standard error; **Q1**: First quartile; **Q3**: Third quartile wall of the EcoHouse; for that reason its temperature was not as high as the outside east and west walls. Additionally, Table 7-2 also reveals that the inside south wall recorded the lowest temperature in comparison with the other inside walls. This was due to the fact that the north side of the EcoHouse gets no direct sunlight, therefore the temperature of the opposite wall (the south inside wall) had less chance to increase compared with the other inside walls.

In order to study the indoor and outdoor temperature at the EcoHouse, the average temperature of the walls on the four sides of the envelope were computed. The results of analysing the EcoHouse indoor temperature readings are presented in the following section.

7.1.2 Indoors temperatures

The characteristics of the data collected from inside the EcoHouse envelope during the whole monitoring period are presented in the following section. Hereinafter the entire period of monitoring will be referred to as the 'all years' period.

7.1.2.1 Indoor 'all years' period analysis

The thermal profile of the indoor temperature of the EcoHouse from March 12, 2008 to November 21, 2010 is presented in Figure 7-2. The gaps in the curve are periods of unrecorded temperature (being some of the missing data, as explained in section 6.4).

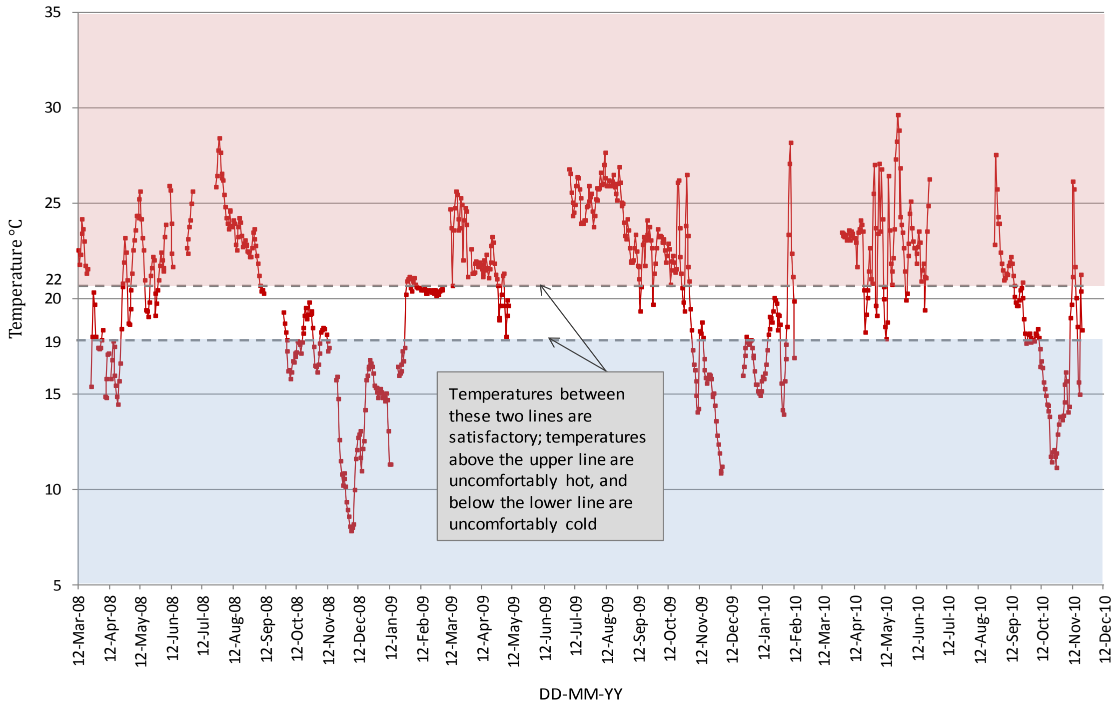

Figure 7-2: Mean daily variations of indoor temperatures, °C (n = 718)

The minimum, maximum, and mean temperatures for the 'all years' sample were computed, and were 7.8°C, 29.6°C and 20.2°C, respectively. The standard deviation (StD) of the averages was 4.1°C. UK practitioners tend to refer to the Chartered Institute of Building Services Engineers' Guide (CIBSE, 2006), which recommends a comfortable temperature range of 19.5 ± 0.5°C in winter and 21 ± 1°C in summer. Figure 7-2 shows that the indoor temperature in the long term, contrary to what would be satisfactory and deemed 'comfortable' (e.g. 19 - 22°C), was very variable, with fluctuations illustrating sharp changes varying between 7.8 – 29.6°C. The fluctuations indicate that there were times with uncomfortable indoor temperatures. On the other hand, the mean temperature of 20.2°C signifies that the temperature inside the

EcoHouse was, disregarding the fluctuations, 'satisfactory' and could be regarded as 'comfortable'. There was no significant difference (t-test, t = 0.163, $P > 0.05$) between the average temperature of the 'all years' sample and the daily sample. However, the standard deviation of 4.1°C shows that there were days with indoor temperatures of 20.2°C ± 4.1°C, which are either lower or higher than the comfortable range. The standard deviation also confirms that the minimum and maximum values could be considered extreme, making the indoor temperatures sometimes much too cool and sometimes much too warm. It is possible that this was due to the influence of the outdoor temperature. In order to compare indoor and outdoor temperatures, the two trends were plotted on Figure 7-3.

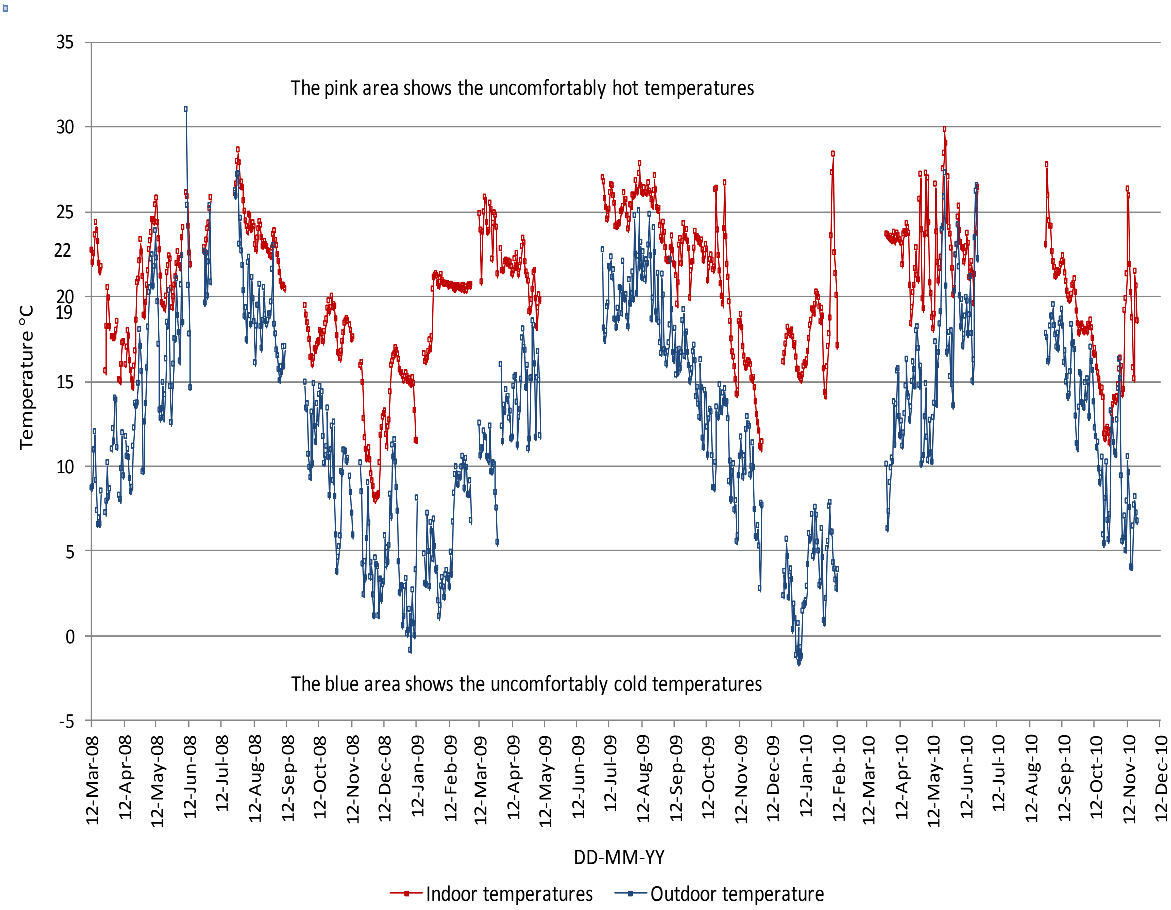

Figure 7-3: The differences between the daily indoor and outdoor temperatures (n = 1,436; 718 (n_{indoor}) + 718 ($n_{outdoor}$))

It is evident from Figure 7-3 that the indoor temperature followed the outdoor temperature fluctuations. However, the indoor temperature, as to be expected, was always warmer in comparison with the outdoor temperature, regardless of whether the indoor temperatures were considered comfortable or not (the variations of indoor temperature are presented in the next section). The indoor temperature that was considered a comfortable temperature forms 28.1% of the entire indoor temperature data, whereas 36.8% and 35.1% of the data was above and below comfortable temperatures, respectively. Through the period of monitoring, the mean of the outdoor temperature was 12.6°C, the lowest daily temperature was -1.8°C and the highest was 30.8°C; thus the indoor temperature, on average, is 7.7°C higher than the outdoor temperature. The minimum and maximum temperatures recorded indoors are slightly warmer and cooler, respectively, than the outdoor temperatures due to the thermal performance of the insulation used in the walls and the floor at the EcoHouse envelope.

The yearly variation in outdoor temperature throughout the monitoring years is shown in Figure 7-4, and their statistical analysis are summarised in Table 7-3.

Figure 7-4: Yearly variation in outdoor temperature
(n = 718; 228 + 273 + 217 number of observations in 2008, 2009 & 2010, respectively)

Table 7-3: Yearly statistical analysis of outdoor temperature (n = 718)

	2008	2009	2010
Minimum (°C)	0.4	-1.0	-1.8
Maximum (°C)	30.8	24.9	27.1
Average (°C)	13.1	12.5	12.2
Median (°C)	12.6	12.7	12.8
Standard Deviation (°C)	6.3	6.1	6.2

In order to distinguish between periods in which the indoor temperature was thermally comfortable or uncomfortable, and to find in which year(s) the most extreme temperatures were recorded, the features of the indoor temperature pattern for the entire monitoring period were studied closely, starting with dividing the 'all years' period into three sub-periods, each representing the indoor temperature in each monitoring year separately.

7.1.2.2 Indoor 'yearly' sub-period analysis:

The yearly variation in indoor temperature throughout the monitoring years is presented in Figure 7-5, together with the yearly statistical analysis in Table 7-4:

Figure 7-5: Yearly variation in indoor temperature (n = 718; 228+273+217 number of observations in 2008, 2009 & 2010 respectively)

Table 7-4: Yearly statistical analysis of indoor temperature (n = 718)

	2008	2009	2010
Minimum (°C)	7.8	10.9	11.2
Maximum (°C)	28.4	27.6	29.6
Average (°C)	19.2	21.2	20.1
Median (°C)	19.3	21.6	20.4
Standard Deviation (°C)	4.4	3.7	3.9

Figure 7-5 together with Table 7-4 show that the minimum and maximum temperatures of the 'all years' sample (7.8°C and 29.6°C, respectively) happened in two different years of the monitoring period; the 7.8°C occurred in 2008; and the 29.6°C in 2010. The figure also shows that the large intervals between the minimum and maximum temperatures in comparison with the average temperatures were a feature of each monitored year. Such results generate hesitation regarding the stability of the internal temperatures in the EcoHouse on a yearly basis. The standard deviation differences in each year, 4.4, 3.7 and 3.9 respectively, raised doubt over whether the 'all years' average temperature still significantly represents the average for the yearly samples. From the t-test, the yearly average of the first two years of monitoring (2008 & 2009) were found to be significantly different ($t = -3.317$, $P = 0.001$, and $t = 4.408$, $p < 0.001$, respectively) from the 'all years' average (20.2°C), but there was no significant difference ($t = -0.524$, $P > 0.05$) between the average temperature of year 2010, and the 'all years' average. This suggests that the indoor temperatures were more stable in 2010 in comparison with 2008 and 2009. Despite this, the minimum and maximum temperatures for each year show that there were times when the indoor temperatures were too low or too high based on the 'comfortable temperatures' recommended by CIBSE. This raises some concerns about whether the minimum and maximum temperatures were being influenced too much by the outdoor temperature, or if there was another factor influencing indoor temperatures. Also, questions arise over whether there were more events with uncomfortable temperatures during the observation period. Occasions on which the indoor temperatures were uncomfortable were not the real focus of this study;

however such events need to be considered in order to identify causes that potentially affect the performance of the heating system.

To address these questions, the yearly sample was divided into monthly sub-periods, as is explained in the following section.

7.1.2.3 Indoor 'monthly' sub-period analysis:

The minimum, maximum and the average temperatures on a monthly basis were computed, and the results are presented in Table 7-5. Although the comfortable level recommended by CIBSE (indoor temperature to be between 19°C and 22°C, as mentioned in section 7.1.2.1) and the fact that all heating system control panels inside the EcoHouse were adjusted for 20°C (see section 6.3.1), it was taken into consideration while studying the indoor thermal conditions that the control panels inside the EcoHouse could be adjusted for a temperature anywhere between 18°C and 29°C and that despite the instruction given to visitors not to change the control panel settings (since the EcoHouse was open to the public as a show case), it was noticed that the adjusted settings on the control panels were occasionally changed. Thus, indoor monthly temperatures, along with the outdoor temperature are shown Table 7-5, and falling in the range between 18°C and 29°C whilst the outdoor minimum temperature was less than 18°C, indicate that heating was being provided to the EcoHouse. Indoor temperatures less than 18°C shown in the minimum and (in some months) in the maximum columns, were still higher than the outdoor minimum temperatures of the

Table 7-5: Indoor and Outdoor monthly statistical measurements during the monitoring period (n = 1,436)

Indoor & Outdoor monthly measurements - °C

		2008			2009			2010		
	Location	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
January	Indoor	Temperatures collection started March 2008			11.3	21.2	16.3	14.2	20.1	17.2
	Outdoor				-1.0	7.9	3.3	-1.8	7.4	2.7
February	Indoor				20.2	21.1	20.5	13.9	28.2	20.1
	Outdoor				0.9	10.4	6.0	2.0	7.7	4.7
March	Indoor	15.4	24.2	20.9	20.4	25.7	23.3	23.4	23.5	23.5
	Outdoor	6.4	11.8	8.5	5.3	12.3	9.7	6.1	9.9	8.0
April	Indoor	14.5	23.2	17.7	18.9	23.2	21.9	18.2	25.5	22.5
	Outdoor	7.8	17.9	11.6	10.8	17.9	13.9	7.1	18.0	13.3
May	Indoor	18.6	25.6	21.6	18.0	21.3	19.9	17.9	29.6	23.4
	Outdoor	12.4	23.7	17.2	11.5	18.4	15.2	9.9	27.1	15.6
June	Indoor	21.5	25.9	23.1	N/A	N/A	N/A	19.4	26.2	22.5
	Outdoor	14.4	30.8	20.5	N/A	N/A	N/A	13.4	26.3	19.9
July	Indoor	25.0	28.4	26.6	23.8	26.8	25.1	N/A	N/A	N/A
	Outdoor	20.6	27.0	24.6	17.3	22.6	19.7	N/A	N/A	N/A
August	Indoor	22.2	26.2	23.6	23.1	27.6	25.7	22.9	27.6	24.9
	Outdoor	15.9	22.8	19.2	16.5	24.9	21.1	16.0	18.1	17.0
September	Indoor	18.7	23.1	21.0	19.4	24.2	22.3	17.7	23.9	20.5
	Outdoor	13.2	17.6	15.8	14.8	22.0	16.9	10.9	19.3	16.1
October	Indoor	15.8	19.8	17.8	19.4	26.5	22.6	11.2	18.4	15.1
	Outdoor	3.6	14.7	10.7	8.5	16.1	12.9	5.2	16.8	11.3
November	Indoor	9.3	18.5	15.0	11.9	20.9	16.0	13.6	26.1	18.1
	Outdoor	2.2	10.8	7.3	5.1	12.7	9.2	3.8	16.1	8.5
December	Indoor	7.8	16.8	12.8	10.9	18.0	15.7	Recording stopped in November 2010		
	Outdoor	0.4	11.4	4.7	2.1	7.9	4.0			

Temperatures shown in boxes are the indoors and outdoors minimum and maximum temperatures (refer to Table 7-3&4).

N/A: Temperatures are not available

same month, thanks to the influence of the insulation, passive solar heating effect, small heat radiation from furniture items, lighting and 'thermal disturbance' due to visitors and so forth. Hence, this suggests that the indoor temperature had dropped due to the lack of indoor heating coinciding with the effect of the cold outdoor conditions. Indoor temperature higher than 29°C only occurred in May 2010 (29.6°C), and could be a result of the control panel being turned up by somebody (perhaps a visitor) to a higher value. In April, October and November 2008, January, November and December 2009, and January, October and November 2010, the average temperature was below the comfortable range, whilst the maximum temperature was considered comfortable. This is due to the possibility of heating being provided, but only for a short period that was not enough to bring the mean into the range, whereby it would be considered comfortable.

In March 2008, and February, May and September 2010, the monthly indoor average temperatures, were in the comfortable range; however, the minimum temperature indicates that an event causing a clearly undesirable temperature occurred. The results of the monthly statistical tests for each year are shown in Table 7-6.

Table 7-6: Indoor monthly statistical tests for each year (n = 718)

	2008		2009		2010	
	t-test	*P*-value	t-test	*P*-value	t-test	*P*-value
January	N/A	N/A	-7.05	<0.001*	-9.45	<0.001*
February	N/A	N/A	7.65	<0.001*	-0.05	0.965
March	1.10	0.289	7.83	<0.001*	65.0	0.010*
April	-5.45	<0.001*	7.20	<0.001*	7.93	<0.001*
May	3.90	0.001*	-0.85	0.421	5.60	<0.001*
June	8.789	<0.001*	D/M	D/M	6.88	<0.001*
July	17.17	<0.001*	27.66	<0.001*	D/M	D/M
August	19.848	<0.001*	31.88	<0.001*	5.80	0.004*
September	1.974	0.074	9.95	<0.001*	1.11	0.276
October	-11.96	<0.001*	8.18	<0.001*	-11.59	<0.001*
November	-7.56	<0.001*	-11.13	<0.001*	-2.56	0.019**
December	-13.16	<0.001*	-5.45	<0.001*	N/A	N/A

N/A: Data not available due to being either before or after the period of data collection

D/M: Data missing

* Significant at 0.01 level

** Significant at 0.05 level

From Table 7-4, it can be seen that March of 2008, May of 2009, and February and September of 2010 were the only months with a monthly average temperature exhibiting no significant difference from the 'all years' average. This shows that the average indoor temperature on a monthly basis throughout most of the monitoring period was not equal to 20.2°C (the mean of the 'all years' sample).

Days on which the indoor temperature ranged between 18°C - 29°C were selected as days when space heating was being provided to the EcoHouse. Despite the indoor temperatures on some of the selected days being outside the comfortable range (i.e. between 19°C and 22°C), those days were still considered in this study as days on which heating was provided, in line with the justification given above. The total sum was 351 days out of 718 days from the outdoor and indoor temperature data set. The selected days are presented in Figure 7-6:

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2010						7			19			
					23	18-20			29-30			
				29	26-31	15			21-26		11	
	13	7	2	29-30	14-18	10-11		4	13-19	3	19-21	
	17-29	05-11	30-31	01-27	01-12	01	N/A	27-30	05-08	06-08	09-16	End of monitoring
2009									24			
			22						21-30		6	
	5	28	12-29	30	6		3	2	10-18	31	11-13	
	27-31	01-28	01-04	01-30	03-08	N/A	07-09	29-30	02-06	01-31	01-03	N/A
2008					17			3				
			14	9	25-30	4		19	12	12	5	
			26-29	23-30	14-21	12-13		13	29-30	18-28	10	
	Monitoring started 12th Mar 08		12-21	05	01-03	02-03	N/A	05	01-10	01	05-08	N/A

The highlighted cells include the sum of the number of days selected from each month

N/A: Days with outdoor temperature less than 18°C, and indoor temperature ranged between 18°C - 29°C were not available

Figure 7-6: Dates on which heating was provided and indoor temperatures were between 18°C - 29°C

The dates shown in Figure 7-6 were then used to fulfil one of the objective of the research (specifically objective 2a.), in order to calculate the performance coefficients of the GSHP in the next chapter.

The variation between indoor and outdoor temperatures during the heating period is represented in Figure 7-7:

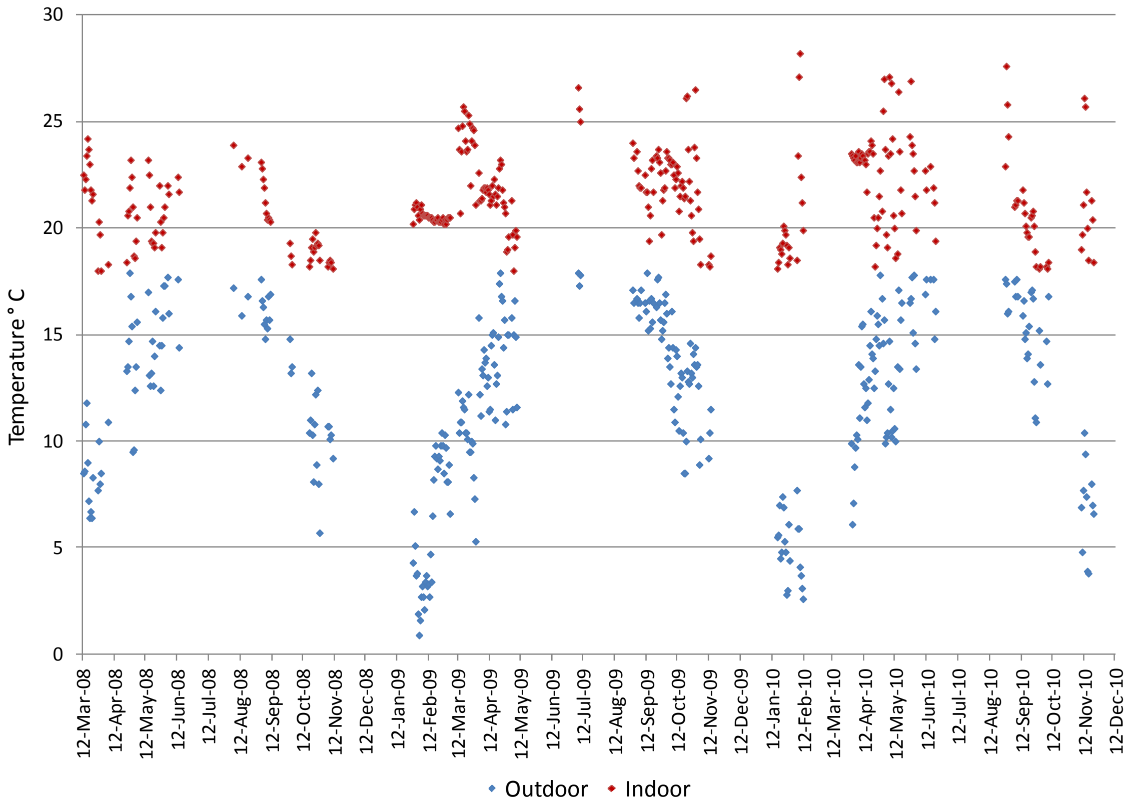

Figure 7-7: Differences between daily indoor and outdoor temperatures for days on which heating was provided to the EcoHouse (n= 702)

During the heating period, the outdoor average temperature was 12.0°C (minimum and maximum temperatures were 0.9°C, 17.9°C), respectively, whilst the indoor temperature showed an average value of 21.5°C (minimum and maximum temperatures were 18.0°C, 28.2°C, respectively).

The ground temperature profiles and the ambient air temperature during the monitoring period are presented in the next section.

7.1.3 The PPS/GSHP and the meteorological temperatures profiles

The PPS/GSHP ground thermal distributions were measured at varying depths: 60mm, 130mm, 200mm and 350mm (as explained in section 6.3.2.1), from 8th August, 2008 to 30th March, 2010. The ambient air temperature during this period was also measured. The next section presents the 'all years' temperature profile.

7.1.3.1 The ground and the ambient air 'all years' period analysis

The patterns of the daily averaged ground temperatures are illustrated in Figure 7-8. The ambient air temperature was also measured during the same period and the mean daily temperatures are also shown in this figure.

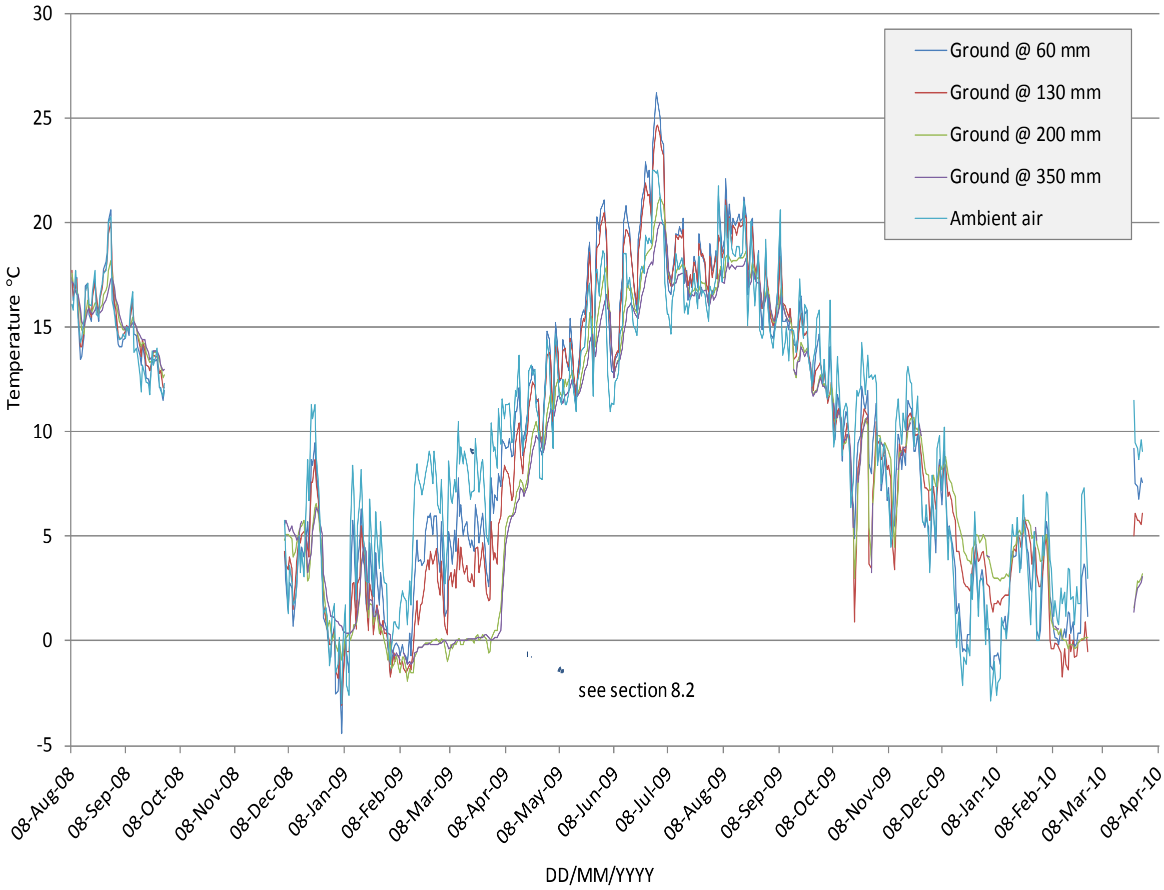

Figure 7-8: Variations of daily average ground temperature and ambient air temperature (n = 2,449)

It is clearly evident from Figure 7-8 that ground temperatures at the four depths have a profile similar to that of the ambient air temperature; there were short-term strong and irregular fluctuations of temperature, caused by the daily changes in weather conditions. Descriptive statistics for the ambient air and the four ground temperatures are given in Figure 7-9, and results are summarised in Table 7-7.

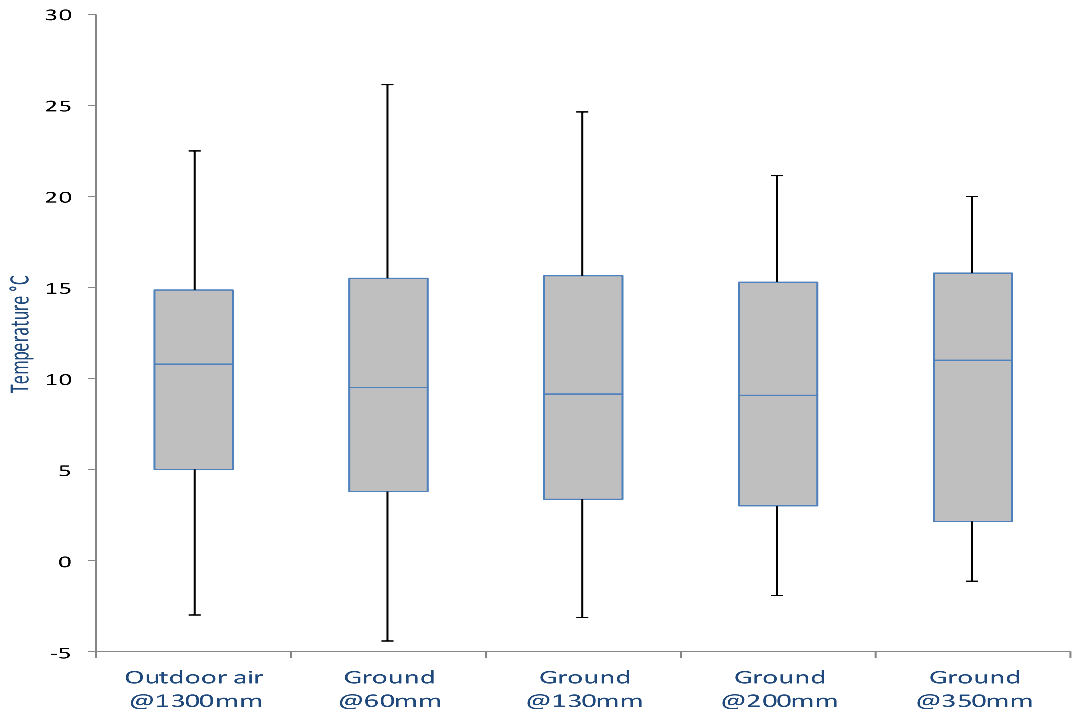

Figure 7-9: The main temperature features of the ambient air and the ground throughout the monitoring period (n = 2,449)

Table 7-7: Statistical analysis of the ambient air and the ground temperatures (°C) throughout the monitoring period (n = 2,449)

	Temperatures throughout the monitoring period				
	Outdoor air @ 1300mm	Ground @ 60mm	Ground @ 130mm	Ground @ 200mm	Ground @ 350mm
Minimum (°C)	-3	-4.4	-3.1	-1.9	-1.1
Maximum (°C)	22.5	26.2	24.7	21.2	20.0
Average (°C)	10.0	9.7	9.5	8.8	9.6
Median (°C)	10.8	9.5	9.2	9.1	11.0
Standard Deviation (°C)	6.0	6.9	6.9	6.6	6.7

Figure 7-9 and Table 7-7 show that the minimum temperatures for all depths were below zero (i.e. stored rainwater was in the frozen state); and that ground temperature nearest the surface (60mm deep) recorded the highest maximum and the lowest minimum temperatures; these characteristics reduced with increased reservoir depth. The figure also shows that there was minimal difference between the averages given for the ground temperature at each depth. The daily average temperature for the four different depths are not significantly different from the ambient air daily average temperature ($t = 3.931$, $t = 4.718$, $t = 8.074$, $t = 10.541$; $p<0.001$, for the four depths respectively).

7.1.3.2 The ground and the ambient air 'seasonal' analysis

Data collected from the ground temperature sensors was divided into the following categories: data collected during summer time (from April to September); and temperature readings collected during winter (from October to March). The seasonal changes of ground temperatures according to the depth are shown in Figure 7-10.

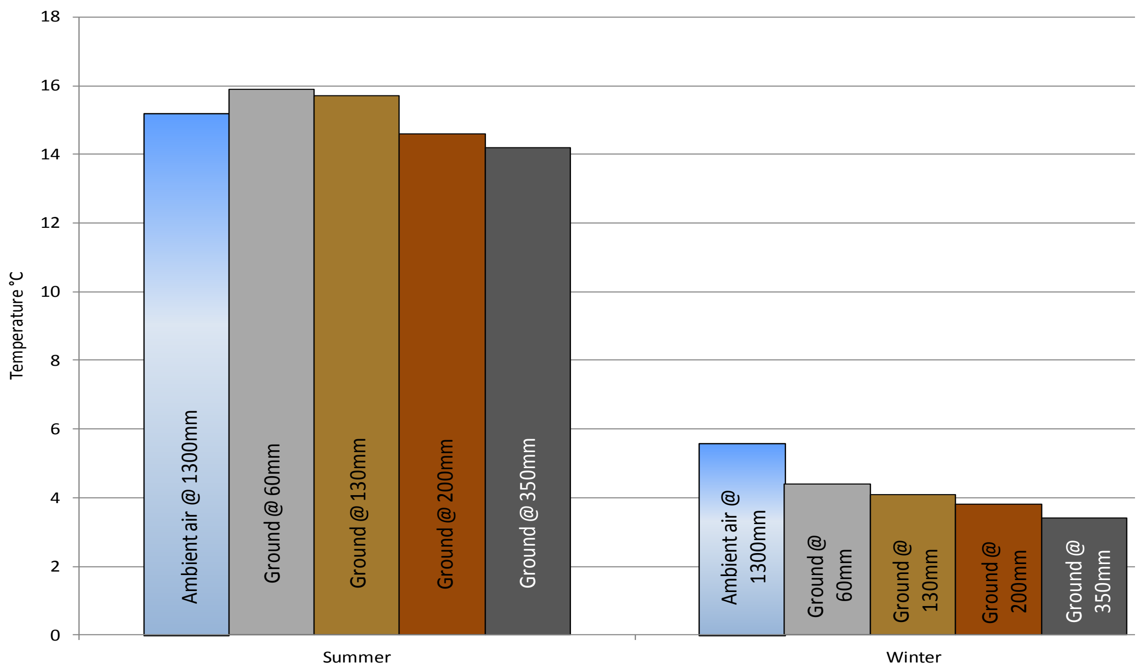

Figure 7-10: Seasonal changes in average ground temperatures (n = 2,449)

Figure 7-10 clearly shows seasonal variations. The average ground temperature at the various depths during the summer season ranged between 14.2 and 15.9°C, whereas they ranged between 3.4 and 4.4°C during the winter season. As can be seen in the figure, ground temperature decreases with the increase in depth in the two seasons, summer and winter. The figure also shows that, during the summer season, the temperature of the ground nearer to the surface (60mm and 130mm deep) is higher than the air temperature, but not in the winter season. These results can be attributed to the effect of the solar radiation hitting the surface of the pavement during summer time causing the surface to be warmer than the deeper reaches, whereas in winter, the strength of solar radiation wanes. Subsequently frozen rainwater (it was observed during the monitoring that the stored rainwater was frozen for parts of the winter season, as can be seen in Figure 7-8; also Figure 7-9 showed that the minimum temperatures were < 0°C) at deeper depths needs a longer time to thaw, which results in the deeper reaches remaining colder than the layers nearer to the surface of the PPS/GSHP pavement.

The average ground temperature at 350mm deep during the summer season was 14.2°C; for winter it was 4.5°C. Meanwhile, the average temperature of the ambient air was 15.0°C and 6.5°C during the summer and the winter seasons respectively. Hence, the GHE is in contact with ground that was 0.8°C cooler than the ambient air temperature during summer time, but also cooler than the winter ambient air by 2°C. This is in contrast with some studies, for example, Healy & Ugursal, 1997; Hepbasli, 2005; Nordell *et al.*, 2007; Ozgener *et al.*, 2007; and Song *et al.*, 2010, which have shown that the ground temperature is cooler in summer and warmer in winter in comparison with ambient air. The fact that the reservoir was at the relatively shallow depth of 350mm, and therefore seems to have been strongly influenced by the ambient air temperature, may be the explanation for the small difference between the ground and ambient air temperatures. However, the observation of ground temperature at the bottom of the reservoir being even lower than the temperature of the ambient air during the winter is a combination of cold climatic conditions and heat extraction during heating operation.

7.1.3.3 The ground and the ambient air 'monthly' analysis

For a closer understanding of the ground temperature dimension, the monthly average temperatures for each ground depth together with the ambient air temperature are plotted in Figure 7-11.

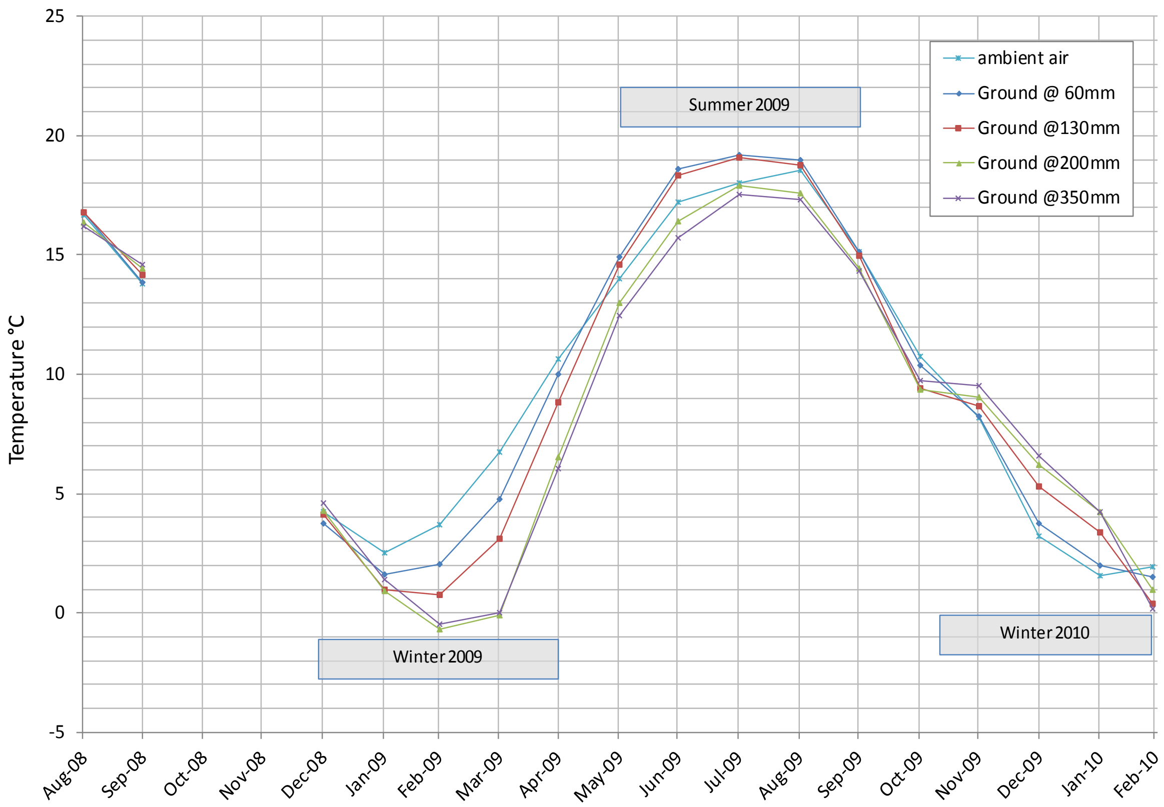

Figure 7-11: Changes in monthly average temperature variations of the ambient air and the different ground depths (n = 2,419)

By plotting the monthly average for ground temperature variations (Figure 7-11), it becomes clear that none of the ground temperatures at the different depths were constant. This is related to the fact that the reservoir was at too shallow a depth, so even the deepest level is still influenced by the climatic conditions. However, the figure does show that, despite the small difference in ground temperature at the different levels, at 200 and 350mm the ground is still cooler in summer and warmer in winter 2010 than it is at 60 and 130mm.; i.e. ground temperatures at 200 and 350mm depth are slightly less affected by the ambient air as they are deeper in the PPS, but it may also be related to the fact that these levels are located at the bottom of the reservoir, where the harvested rainwater is stored, i.e. it could be the influence of the different physical properties of the medium, since the temperature of the ground at a given depth is not only dependent on climatic conditions but is also strongly influenced by the surrounding media (Kavanaugh and Rafferty, 1997). Interestingly, the thermal condition of the ground during winter 2009 was different to that of winter 2010, as the temperatures of the ground at the bottom of the reservoir were cooler than they were at the top part of the reservoir (this specific period is marked with a dotted circle in Figure 7-8). This is attributed to heat extraction from the ground consecutively during winter 2009 which caused a drop in ground temperature mainly where the coil was placed (between 200mm and 350mm below the surface of the reservoir) – the thermal condition of the ground throughout the heat extraction period will be explained in the next chapter, section 8.2. The ground temperature at the depth of 350mm was 3.3 – 1.7°C lower/higher than the monthly average ambient air temperature during most of the monitored period. Sometimes the difference between them was as high as 6.7°C.

Table 7-8 tabulates the main annual monthly characteristics found for each ground level, together with those for the ambient air, and shows temperature differences ranged between 0.8°C and 7.4°C.

Table 7-8: Variations of average monthly values of ground and air temperatures at several depths throughout the monitoring period (n = 2,449)

	Monthly measurements														
	Ground @ 60 mm			Ground @ 130 mm			Ground @ 200 mm			Ground @ 350 mm			Ambient air @ 1300 mm		
Month	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Jan	-6.3	7.6	1.8	-4.5	6.7	2.2	-1.5	5.9	2.6	0.4	5.4	1.8	-6.2	9.8	2.4
Feb	-3.6	9.5	1.8	-4.2	6.5	0.6	-3.2	5.6	0.1	-1.4	0.7	-0.3	-6.0	13.4	3.8
Mar	-1.0	11.6	5.2	-1.6	9.0	3.5	-1.6	4.0	0.3	-0.5	3.2	0.4	-1.2	16.5	7.7
Apr	1.1	21.7	10.0	0.2	17.5	8.8	0.0	11.2	6.5	0.0	10.0	6.1	1.6	22.7	10.8
May	6.6	32.9	14.9	8.6	27.7	14.6	10.0	18.0	13.0	10.2	15.5	12.4	4.1	27.9	13.6
Jun	9.3	35.1	18.6	9.6	29.7	18.3	11.4	21.5	16.4	12.0	19.0	15.7	6.2	31.2	16.3
Jul	11.6	37.8	19.2	13.3	32.6	19.1	15.5	22.7	17.9	16.0	20.4	17.5	10.2	31.8	17.4
Aug	9.6	31.4	18.0	11.2	27.2	17.9	14.0	19.8	17.1	14.8	18.4	16.8	8.3	29.6	17.5
Sep	7.4	23.9	14.5	8.8	21.6	14.6	10.8	17.8	14.4	11.6	17.4	14.5	5.1	27.3	14.3
Oct	2.8	16.1	10.4	-0.2	14.8	9.4	1.6	13.0	9.4	3.3	12.8	9.7	1.4	18.9	11.6
Nov	3.7	14.0	8.3	1.0	13.7	8.6	3.6	11.0	9.0	8.1	10.6	9.5	1.5	16.1	9.1
Dec	-2.3	10.2	3.7	-1.3	9.1	4.8	-0.1	8.9	5.3	1.2	8.5	4.9	-5.3	13.0	4.1

The minimum temperatures for the various depths recorded during cold months (between December and February) ranged between -6.3 and 1.2°C, and the average temperatures for those months were above zero except the ground at 350mm being the only depth with an average temperature below freezing point, in the month of February in all the monitored years. To study the relationship between the temperature of the ambient air and the layers beneath the paved surface of the PPS/GSHP in summer and winter, a further analysis was performed as detailed in the next section.

7.1.4 The impact of climatic conditions and ambient air temperature on the shallow PPS/GSHP

Although ground temperature observations were recorded for more than 19 months, only the days on which the highest and lowest ambient air temperatures were recorded during monitoring are the days that are focused on in this section in order to investigate the differences between the subsurface temperatures at various depths. The highest ambient air temperature was recorded in summer 2009, on 1st July, reaching 31.8°C at 15:50; whilst the lowest ambient air temperature was -6.2°C, recorded on 7th January 2010 at 06:20 (recorded from the sensor located at 1300mm from the surface of the pavement). Figure 7-12 plots the changes in ground temperature at the four depths on these two days.

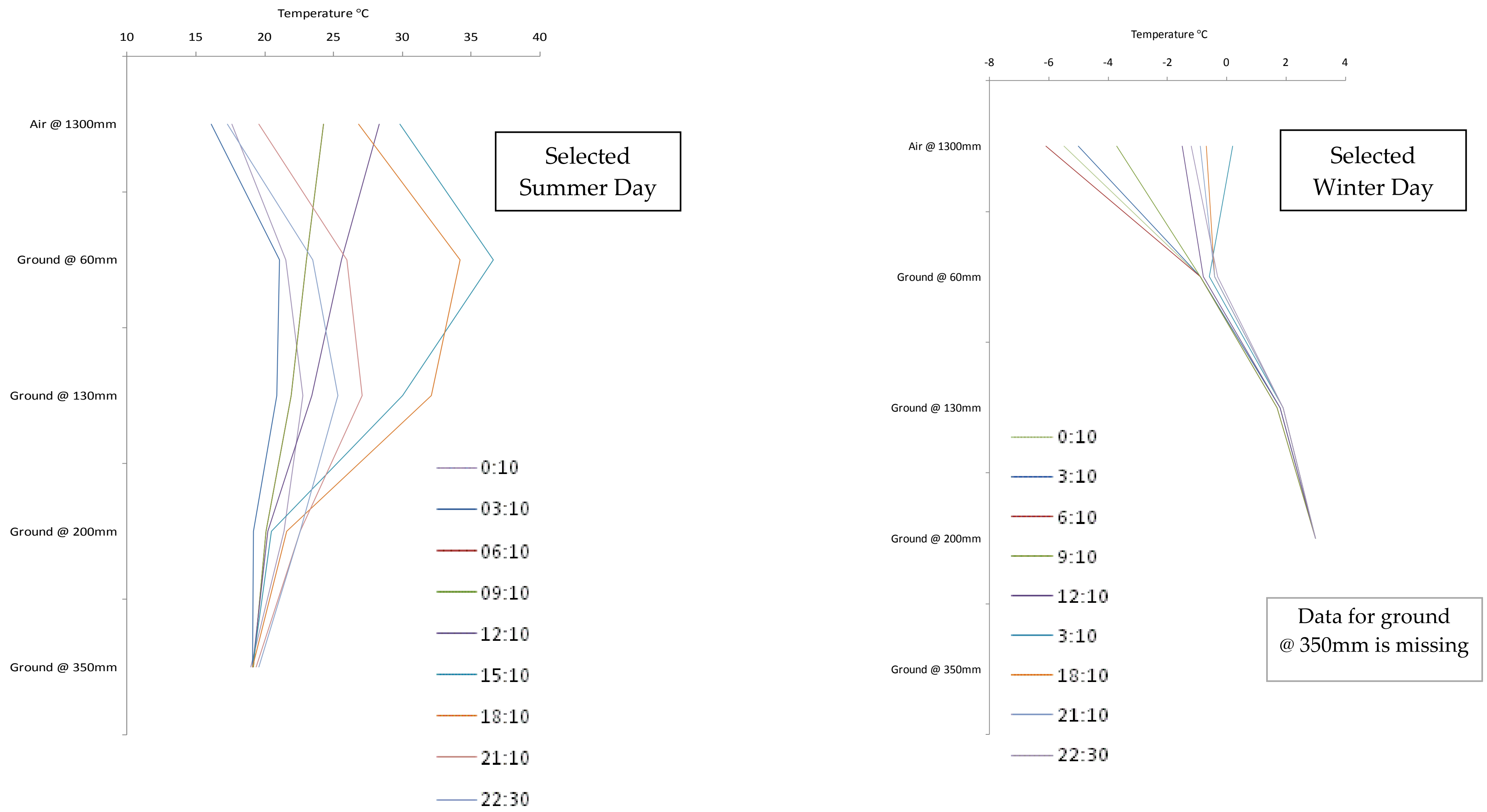

Figure 7-12: Air and ground subsurface temperature variations in summer (01/July/2009) and winter (07/January/2010); (n = 81)

The mean value for the ambient air on the selected summer day was 22.4°C, while for the winter day it was -2.6°C. As can be seen from Figure 7-12, there were clear differences in ground temperature at the four depths on the summer day, but on the winter day the variation was minimal. The differences on the summer day were mainly in the top two layers at 60mm and 130mm due to the influence of the ambient air temperature, together with afternoon solar radiation, particularly during the period 14:00 - 17:00, as it was a clear, sunny day (wunderground.co.uk, 2012). On the other hand, the ground temperature at a depth of 60mm, during the cold day, had a temperature varying between -0.3 and -0.9°C over the whole day; this is probably because the ground surface temperature dropped due to the influence of very cold air, or could be due to the ground being covered with snow or frost, which not only would have prevented the solar radiation reaching the pavement surface, but would also have impeded convection and radiation heat loss (Wu *et al*., 2010). The temperature of the ground surface, however, was higher than the ambient air temperature for most of the day. It is clear from the figure that, on the selected days, the ground temperature varied less at a deeper depth. The ground temperature at the bottom of the reservoir when compared with the air temperature was cooler throughout the hot day and warmer during the cold day.

As illustrated in the figure, on the summer day, when the heat pump should have removed heat from the building and injected it into the ground, the mean values at 200mm and 350mm (where the coil was placed) were 20.4°C and 19.2°C respectively, i.e. cooler than the mean value of the ambient air by ~ 2°C and ~3°C respectively. In winter, when the heat pump had to supply heat, the depth of 200mm (temperature data for Ground @ 350mm was missing) was

3°C, i.e. only 5.6°C warmer than the mean value of the ambient air on that particular day. This indicates that the ground layer in which the coil was placed was acting as a heat source in winter, and that it can act as a heat sink in the summer season. Furthermore, it indicates it is possible for such a PPS/GSHP system to have a higher CoP than an ASHP system (as explained in section 5.2). However, this forces the heat pump to work at lower efficiencies when a horizontal heat exchanger is used in such setup. The depth of the reservoir in this study (350mm) was not enough so that the ground temperature remained constant and to avoid the underground temperature being influenced by the overlying air temperature. It was observed during the monitoring that there were times when the temperature of the stored rainwater was influenced by cold ambient air temperature, resulting in the temperature of the stored rainwater being so low sometimes that it froze. Some drop in ground temperature may happen when snow at the surface of the pavement melts and the runoff infiltrates through the pavement into the cold ground layers. The initiation of ice thaw under the surface of the pavement occurs later than it does above the pavement. On such occasions, the temperature of rainwater is too low to provide energy to the system; this is demonstrated in next chapter, section 8.1.

The thermal condition of the ground plays a significant role in the efficiency of the GSHP system. In heating mode, if the heat source is warmer and as a result the heat transfer fluid is at a higher temperature, the heat pump needs less power to compress the working fluid, making the heat pump system more efficient. Hence, a ground temperature of 4.4°C warmer than mean value of ambient air, which the coil gains heat from, will not support a high efficiency.

Summary

The collected data is set out in this chapter in order to present specifically the temperature variations inside the EcoHouse envelope, and at the four depths below the PPS/GSHP surface, that occurred during the monitoring period. The ambient air temperature readings collected during the monitoring were also presented.

It was determined that during the monitoring period, the mean indoor temperature was 20.2°C, whilst the average outdoor temperature was 12.6°C. Although the mean indoor temperatures seemed satisfactory (over the monitored period as a whole) and would be deemed comfortable according to the CIBSE, the analysis showed a wide variation in the range of the daily temperature. Thus, a yearly and a monthly analysis were performed. The results revealed that the indoor mean temperature throughout most of the observation period was significantly different from the mean of the 'all years' sample (20.2°C). Furthermore, most of the minimum and maximum temperatures calculated from the indoor temperature readings on a monthly basis were found to be outside the 'comfortable' range. This signifies that there was relatively little thermal stability inside the building. Based on this conclusion, and given that the aim of the current research is to study the performance of the PPS/GSHP for providing heat to the domestic setting, the days on which heating was being provided to the building were filtered out from the entire building data set. A total of 351 days on which heating has been provided to the EcoHouse was determined. The indoor mean temperature for those selected days was 21.5°C, whilst the outdoor mean temperature was 12.0°C, with a minimum temperature of 0.9°C. This indicates that the system

can meet the space heating requirements of a 3-bedroom detached house located in a region subject to cold winter temperatures.

In regards of the ground temperature, the 'all years' analysis showed that the ground temperatures at the four depths were strongly influenced by the ambient air, and there were no significant differences between the mean temperatures of the ground at the four depths and the ambient air. The seasonal effect showed a difference of around 12°C between ground temperature in winter and summer seasons. Further analysis, determined that ground temperature at the bottom of the PPS/GSHP reservoir in comparison with the ambient air was cooler on a hot day, and was warmer during a cold day. Meanwhile, the results of the seasonal analysis showed that the ground temperature at the bottom of the reservoir was cooler than the air temperature in summer, but also cooler in winter.

The outcomes of this chapter were used in order to study the performance of the integrated system, as demonstrated in the next chapter.

Chapter 8 : The thermal performance of the shallow PPS/GSHP and the results of harvested rainwater level

Introduction:

Temperature data collected throughout the monitoring period were analysed in Chapter Seven. The results from these analyses were used in this chapter in order to calculate the Coefficient of Performance (CoP), and to investigate the impact of extracting heat through the GHE coil on the temperature of the surrounding ground over the longer term. It was also of interest to ascertain whether the PPS/GSHP reservoir has an effect on the temperature of the air directly above it. This chapter also presents the results of measuring the level of the harvested rainwater in the PPS/GSHP.

8.1 Heating performance of the integrated PPS/GSHP system

The CoP of the PPS/GSHP system was determined in order to assess the efficiency of the system and to evaluate the daily performance of the heating operation (see section 5.2). The latter was not directly measured, but it can be estimated from the heat source (the ground) and the indoor temperature observations whilst heating was being provided to the building envelope. The CoP for the system was determined by equation (8) shown in section 5.2. The CoP depends strongly on the temperature difference between the source of heat (the PPS/GSHP reservoir) and the conditioned space (the EcoHouse envelope). During heating mode, as explained in section 5.1, the system extracts thermal energy from the ground to be injected into the space to be conditioned. The ground is considered as the 'heat' source, even though it is clear that this source is relatively 'cold'. Although in the methodology chapter, section 6.3.2.1, the GHE coil was shown to be placed in the PPS/GSHP at a depth of between 200mm and 350mm, it should be borne in mind that in accordance with the usual slinky coil arrangement for the most part the larger area of the coil is in contact with the ground at the bottom of the reservoir, and only small parts of the coil are sticking out at the depth of 200mm. Hence, the ground temperature observations obtained from the thermistor installed at 350mm deep reflect the ground temperature where heat extraction was mainly processed.

Although the monitoring period was for almost three years, only the days on which heating was provided to the EcoHouse (351 days, see Chapter Seven, Figure 7-6), were involved in the CoP calculations. However, several ground temperature readings at 350mm deep, for the days on which heating was provided, were missing due to emergency electricity shut down, amongst others (as explained in section 6.4). This resulted in a smaller number of 'usable' days for calculating CoP, 163 days instead of 351. During those days the mean temperature for the ambient air and for the ground at a depth of 350mm were 11.9°C (ranging between 0.9 and 17.9°C) and 6.9°C (ranging between -1.1 and 18.8°C), respectively. The CoP values were calculated and plotted against ground temperature as given in Figure 8-1, values varying between 0.9 and 4.8 with an average of 1.8.

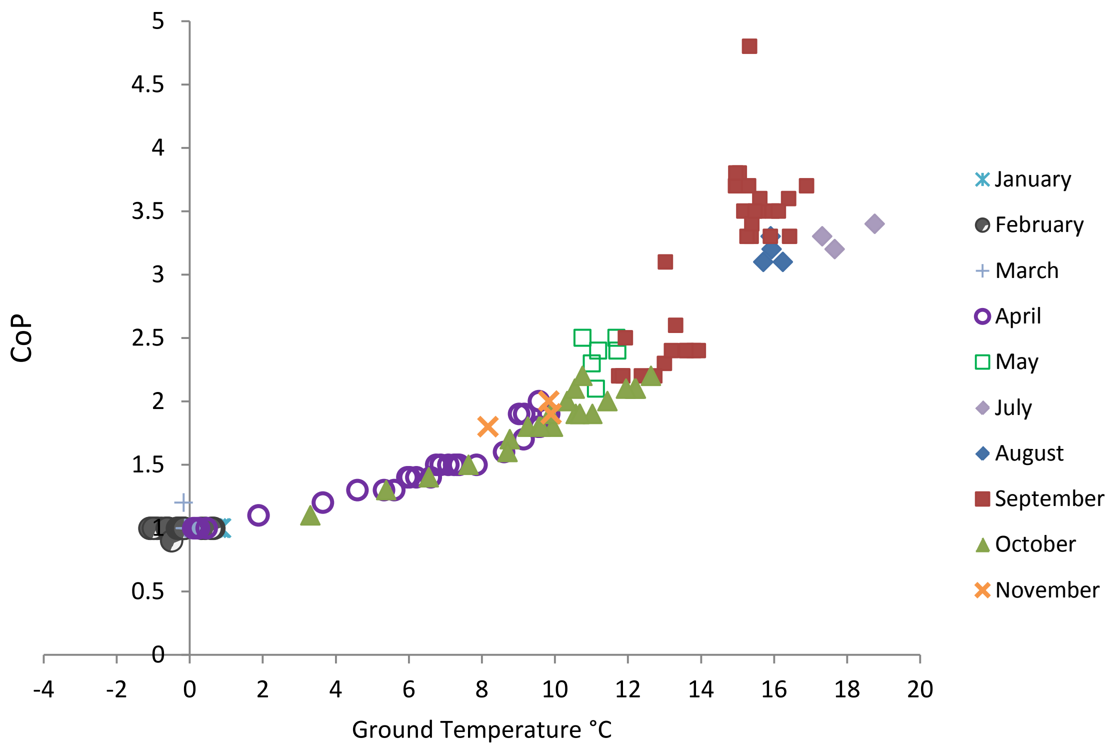

Figure 8-1: Coefficient of Performance (n = 163)

The highest value of CoP was 1.4 for January, 1.0 for February, 1.2 for March, 2.0 for April, 2.5 for May, 3.4 for July, 3.3 for August, 4.8 for September, 2.2 for October, and 2.0 for November (there was no satisfactory data to calculate CoP for neither June nor December). It is clear from the figure that CoP values increased with the increase of ground temperature. Since ground temperature is strongly influenced by climatic conditions (as was concluded in the previous chapter), thus the ground temperature increases with the increase in ambient air temperature, and this contributes to increased performance, and vice versa, as can be seen in Table 8-1.

Table 8-1: Changes in CoP values throughout the monitored period (n = 163)

	Average ambient temperature (°C)	Ground temperature at 350mm (°C)	Indoor average temperature	CoP
(summer 08) 13 Aug 08 - 29 Sep 08	16.1	15.4	21.5	3.5
(winter 08 - 09) 27 Jan 09 - 29 Mar 09	7.4	-0.1	21.7	1.0
(summer 09) 01 Apr 09 - 30 Sep 09	15.1	10.3	21.8	2.2
(winter 09 - 10) 01 Oct 09 - 30 Mar 10	11.3	8.5	21.8	1.7

In order to assess possible relationships between the CoP values and the ambient air and ground temperatures, a correlation analysis was performed. CoP is statistically correlated with the outdoor temperature (0.700**) and correlates closely with ground temperature (0.926**); the climatic condition exhibits a correlation (0.787**) with ground temperature at the 350mm depth (** correlation is significant at the 0.01 level).

As can be seen from Figure 8-1, for the days on which the ground temperature was less than 1°C (varying between -1.1 and 0.9), the CoP value was 1.0 or less. This indicates that heating provided to the EcoHouse on such days was derived completely from the electricity mains without any heat energy being derived from the ground. The days on which heating was provided, and the temperature of the ground was greater than 1.9°C (the next higher ground temperature after 0.9°C was 1.9°C; there were no recorded ground temperatures between 0.9 and 1.9°C), the CoP varied between 1.1 and 3.8, with an exceptional day with CoP of 4.8, all together totaling 101 days. The latter CoP was achieved when the indoor temperature was 19.4°C and ground temperature was 15.3°C; the lower heat load and the higher water temperature combined allowing the combined system to reach the CoP of 4.8. The lowest CoP value (1.1) (this is the lowest value of the CoP after the days on which CoP value of 1 were extracted) occurred when the daily average for the ground temperature was 1.9°C, and the indoor temperature was 21.8°C.

The mean CoP value during the days when ground temperatures were greater than 1.9°C was 2.3, which is consistent with values reported in a UK study arranged by the Energy Savings Trust (Energy Saving Trust, 2010), in which 54 GSHP installations were monitored and the mid-range GSHP efficiencies were between 2.3 and 2.5, with the highest figures reaching over 3.0. The CoP value obtained from the PPS/GSHP system provides evidence of the reliability of the combined system under conditions when the stored rainwater is less influenced by cold conditions.

The effect of extracting heat through the GHE coil on the thermal condition of the surrounding ground is detailed in the next section.

8.2 Ground temperature assessment during the heat extraction period

From the CoP point of view, the PPS/GSHP system provided the building envelope with an average value of 2.3, which is arguably an adequate rate in a small domestic setting. The question remains, however, whether the 350mm deep reservoir is adequate for long-term operation, and whether it does or not cause a degradation of the ground thermal profile on prolonged operation. In order to investigate this a long period of continuous heat extraction from the ground should be investigated. However, the heat pump, as explained previously (section 7.1.2.3), only operated intermittently, which resulted in space heating being provided continuously only for a couple of days at a time (see Figure 7-6). The longest period of consecutive days with heating operation provided by the heat pump was from 27th January 2009 to 30th April 2009, with a short stop in data collection, from 5th to 11th of March 2009; therefore this was the period selected for the current investigation. The patterns of daily average temperatures for the ambient air, and the ground at the four depths (60mm, 130mm, 200mm, 350mm), whilst a continuous heat extraction from the ground at a mean CoP of 1.2 was in progress are all presented in Figure 8-2.

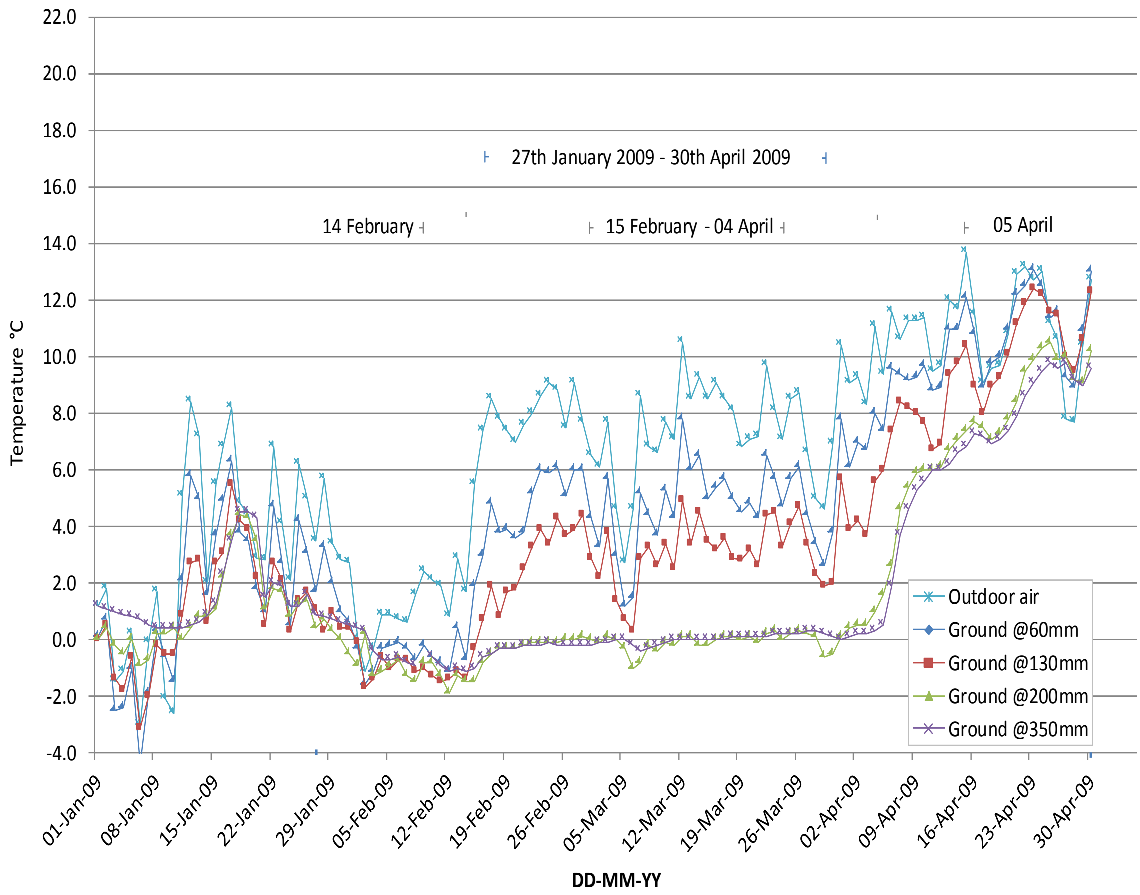

Figure 8-2: The relation between the temperatures of the ambient air, and the ground at various depths during a period of a continuous heating operation (n = 628)

In order to investigate the variation of the temperature of the ground after the GSHP system has been operating for an extended period, the readings for the ambient air and the ground at the four depths in Figure 8-2 are given from 1st January to 30th April, 2009. Over the period from 1st January to 26th January (no heat extraction), the ground temperatures at all depths were following the pattern of the temperatures of the ambient air. From 27th January 2009 to 30th April 2009, in which the process of heat extraction was taking place, a different scenario was observed. For a closer investigation, this period is divided into three sub-periods. During the first 19 days (from 27th January to 14th February) of heat extraction, the ground temperatures at the four depths declined to below zero whilst the ambient air temperature also decreased. Between 15th February and 4th April, while the temperature of the upper two depths increased as the ambient air temperature increased, the temperature of the lower two depths increased slightly by 1°C at first, then remained almost constant at 0°C for several days, which could be related to the phase changes (freezing/melting processes) happening at that depth (Eslami-nejad and Bernier, 2012; Gonzalez *et al*., 2012). From 05th April to 30th April, whilst a further increase in ambient air temperature occurred (about 3°C), the ground temperatures at the depths of 200mm and 350mm did also increase, but still remained lower than the ground temperatures at 60mm and 130mm.

During the period of heat extraction (From 27th January 2009 to 30th April 2009), the temperature of the ground at the bottom of the reservoir (at 350mm deep) was lower than ambient air temperature, and ground temperatures at depths 60mm and 130mm, on average, by 5.5, 3.6, and 2.3°C, respectively. The small rebound in ground temperature occurring where the GHE was placed can be attributed to the effect of increasing solar radiation near the ground surface (Esen *et al*., 2006; Xi *et al.*, 2011), and / or could be a result of a lower demand for heating (in line with the increasing ambient air temperature), and therefore correspondingly less heat extraction (Gonzalez *et al*., 2012). On the other hand, the low temperature at 200mm and 350mm is, apart from the influence of the cold ambient air, most likely because of the

GHE coil extracting heat while the anti-freeze fluid was circulating between these two depths (Gonzalez *et al.*, 2012). Hence, extracting heat continuously from the ground did contribute to an underground temperature drop.

The fact that this study took place in an uncontrollable 'real life conditions' environment meant it was not possible to remove the influence of the ambient air. Thus, the drop in ground temperature at 200mm and 350mm could be also due to the effect of cold ambient air, since it was demonstrated in the previous chapter, section 7.1.3, that the shallow reservoir was strongly affected by the climatic conditions.

The other purpose of collecting ground temperatures was to study the impact of the PPS/GSHP system on the immediate thermal environment. This is discussed in the following section.

8.3 The impact of the PPS/GSHP on the thermal environment

In order to understand the influence of the rainwater stored in the PPS/GSHP on the thermal conditions occurring at the surface of the PPS/GSHP pavement due to evaporation processes, the ground temperature observations collected on 1st July 2009 are presented in this section since the highest ambient air temperature was recorded on this date (the thermal properties of this day are demonstrated in the previous chapter, section 7.1.4), so it is more likely for evaporation process to happen. To facilitate comparison, the air temperatures at 50mm and 1300mm above the surface of the PPS/GSHP (see section 6.3.3) for the same date are also given in this section. Figure 8-3 depicts the vertical profile of the ambient temperature; the temperature of the air near the surface of the pavement; and the temperatures of the ground at 60, 130, 200, and 350mm under the surface of the PPS/GSHP every 6 hours. The selected times to display the observations were at 06:10, 12:10, 18:10 and 22:30 hours. The 6 hrs interval was not complete at 22:30hr since temperature readings after this time were missing for the reasons explained in section 6.4. The distinct times mentioned above were selected since different forms of thermal atmospheric characteristic at the four ground depths could be found; sunrise just after 06:10 hrs; 12:10 hrs was around noontime with the highest downward solar radiation; 18:10 hrs was before sunset, and a range of cooling processes for the different surfaces can be observed during this time of a day; and 22:30 (approaching midnight) is when the formation of a stable stratification in the air layer near the ground surface is taking place.

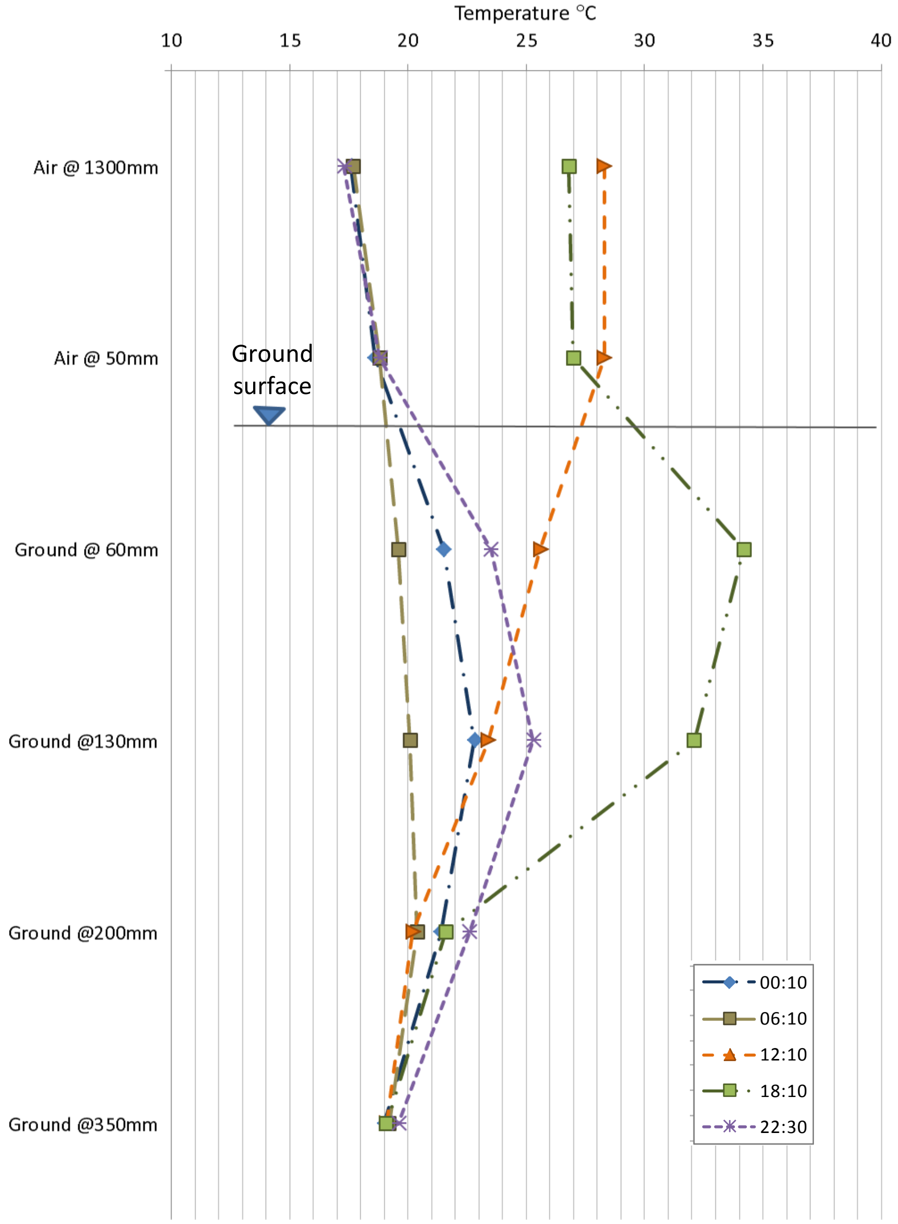

Figure 8-3: A vertical profile of the ground at the four specified depths and the air temperatures on 1st July, 2009
(This particular date was selected since it recorded, during the monitoring period, the highest ambient air temperature); n = 36

(Not to scale)

(Due to data missing – as explained in section 6.4 – temperatures taken at 22:30 were used instead of 24:00, which is less than 6 hours)

Figure 8-3 shows that during the daytime, whilst the temperature of the air at 1300mm above the PPS increased by 10.6°C, the temperature of the ground at 60mm below the surface increased by 14.6°C. The temperature at the 60mm depth varied between 19.6 and 34.2°C. The variation reduces as the depth increases; so at the depth of 350mm, the ground temperature ranged between 19.1°C – 19.6°C since, at this depth, heat coming through the surface does not transfer efficiently because the sub-base material would prevent the solar energy from penetrating.

During the night from 00:10 to 06:10 the ground temperature near the surface (at 60mm depth) decreased from 21.5°C to its lowest value of 19.6°C, due to heat loss of long wave radiation (terrestrial radiation). During the day, and while sunlight is hitting the surface of the pavement, the ground temperature at 60mm deep increased markedly; it was higher by 6°C at 12:10 hr than it was at 06:10, and gained 8.6°C more by 18:10 hr. This is due to extensive heating at the surface by the absorption of the incoming solar radiation. At 22:30 hr, ground temperature at 60mm cooled by 10.7°C from its value at 18:10 hr. Thus, after sunset the temperature of the surface of the pavement declined due to the reduced solar radiation intensity. At the same time of the day, the air temperature at the 50mm height just above the surface of the PPS was reduced as well; however, its temperature was still slightly higher than the air temperature at 1300mm. This indicates that the heat stored in the pavement was still being released. This is in contrast with the conclusion reached by Asaeda & Vu (1992), namely that after sunset the temperature of the ground surface decreases significantly and could possibly become lower than that of the atmosphere; subsequently the surface begins to cool the overlying atmosphere. In the case of this study, as Figure 8-3 shows, the pavement surface temperature did not get cooler than the atmosphere temperature. This is probably due to a number of factors: 1) since there had been no rain on this particular day, the pavement blocks were dry, and thus there would have been no evaporation at the surface, the blocks could therefore have heated like an impermeable pavement, subsequently contributing to increasing the temperature, especially at the shallow 60mm depth; 2) the fact that the channels are filled with coarse gravel, which is unable to retain rainwater for extended periods of time, and a fast-drying surface after rainfall, the potential for evaporation from the surface is consequently reduced; 3) due to the Inbitex composite layer preventing evaporation from occurring (Gomez-Ullate *et al.*, 2010).

With regard to the PPS/GSHP reservoir, an important issue was whether the GHE coil was permanently submerged in the harvested rainwater; the results of measuring the level of the stored rainwater are also given in the next section.

8.4 Results of measuring rainwater level in the PPS/GSHP reservoir

To facilitate better performance in terms of the extraction of heat from the surrounding medium, the coil should be submerged in the stored rainwater as previously explained (section 6.3.2.2). Therefore, the level of the stored rainwater inside the PPS/GSHP was monitored. Results are presented in Figure 8-4.

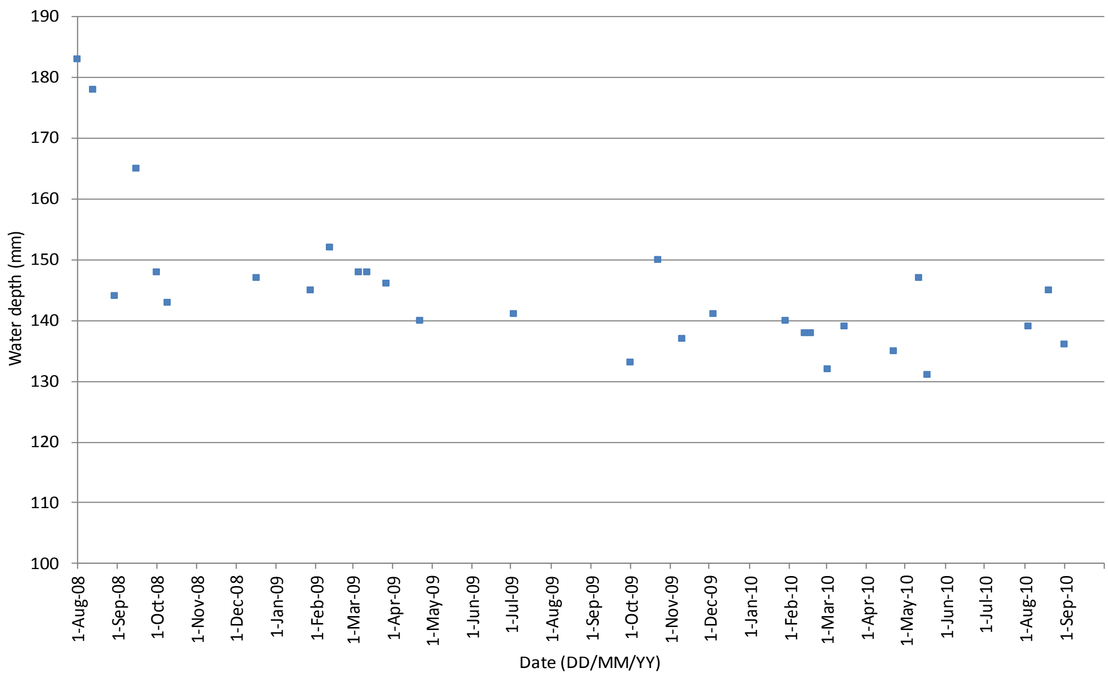

Figure 8-4: Levels of stored rainwater in the PPS/GSHP system (n = 29)

As can be seen from Figure 8-4, the level of the rainwater harvested in the PPS/GSHP was on average at a height of around 140mm. The highest recorded level of the stored rainwater was 180.2mm; this was at an early stage of monitoring the rainwater levels. It was also after the PPS/GSHP reservoir had received runoff after periods of heavy rain that was also collected from the two adjoining roofs (see section 6.2.2). Through monitoring rainwater levels, it was observed that there was a leak in the PPS/GSHP reservoir since it was found that the level of the stored rainwater was rapidly decreasing at the beginning of the curve, followed by fairly constant level at around 140mm. The reason for this is likely to be a gap(s) in the impermeable SC membrane layer on the side(s) of the reservoir, probably caused when a 10-ton cherry-picker truck stood on the pavement during construction work. This resulted in a weakness in the welding joints causing the stored rainwater to discharge out through the gap(s). As was mentioned in Chapter Three, section 3, the PPS was designed for light traffic loading only, so as to preserve the structural integrity of the permeable block paving and the sub-base. Additionally, it was more likely that the gap(s) became larger as time went by since the level of the stored rainwater near the start of the monitoring period during 2008 was measured above 180mm, never exceeded 152mm in 2009, whereas the highest level by 2010 was 147mm. Hence, the top part of the GHE coil at the depth of 200mm was not always submerged in rainwater i.e. was exposed to climatic conditions.

Furthermore, during the rainwater level measurements, it was observed that, at times, the stored rainwater was frozen. Interestingly, the rainwater harvested in the PPS *without* the GHE was never found to be frozen; this is discussed in the following chapter.

Summary

The performance coefficient of the heat pump was determined using data recorded on days on which heating was being provided to the EcoHouse and available temperature data collected from the ground, and was found overall to have a value of 2.3. It was found from analysing the data that there is a strong correlation between the air temperature, the ground temperature and the CoP. It was also demonstrated that when the ground temperature is 1°C or less, the PPS/GSHP cannot provide enough efficiency that would lead to lowered consumption of electricity to meet the heating demand.

Additionally, it was found that the ground temperatures at the depths at which the GHE was located below the surface, during the period of continuous heat extraction, remained the lowest when compared with ground temperatures at the upper reaches nearer the surface. Nevertheless, the strong influence of the ambient air on the ground temperature has been a complicating factor in terms of the possibility of being certain that the changes in ground temperature where the coil is placed were only due to heat extraction, since it could also be because the water stored at the bottom of the reservoir required a longer time to warm up than the upper layers did, which possibly coincided with the period of continuous heat extraction.

The impact of the PPS/GSHP on the immediate environment, particularly in terms of any impact on its thermal profile, was one of the objectives of this study. The hottest day during the monitoring was selected to see whether any evaporation process taking place at the surface of the pavement would cause any changes in the temperature of the air directly over the pavement. It was discovered that the PPS/GSHP had no cooling impact on the atmosphere, with the reasons for this given in section 8.3.

One of the conclusions of this part of the study is that a leakage in the reservoir due to a gap(s) caused by excessive loading on the pavement surface led to some of the stored rainwater discharging out into the surrounding soil; the rainwater level in the reservoir was continuously around 140mm, lower than had been expected, but also too low to cover the top parts of the coils.

Chapter 9 : Discussion

Introduction:

The structure of this chapter is around the aims and objectives presented in section 1.3.1 which were set out so that a full picture of the performance of a PPS/GSHP combined system under real-life conditions is concluded by the end of the study; this included the validity of installing the integrated system in a shallow reservoir in the local climate and in an uncontrolled environment; investigating the potential influence of continuous heat extraction from the ground on the thermal conditions of the ground under realistic conditions and what effect this would have on the performance of the system; determining the coefficient of performance of the GSHP used in the integrated system; and whether comfortable conditions for habitation inside the EcoHouse are provided all year round.

Combining the PPS and the GSHP was suggested by Hanson Formpave and has been applied so far only under laboratory conditions by Grabowiecki (2010) and Tota-Maharaj (2010), in which it was concluded that the PPS/GSHP pollutant removal performance was very high even when the influent was highly polluted in order to reflect the extreme worst-case scenario of a storm event, and that the presence of geotextiles resulted in a significant reduction of contaminants when compared to PPS systems without ($p<0.05$). The lab studies also indicated that up to 99.99% of all physiochemical and microbial water quality parameters decreased significantly. Furthermore, the studies revealed that a low and insignificant correlation was found between temperature fluctuations and waterborne bacterial pathogen numbers. The laboratory work also included CoP calculations which are given in this chapter, section 9.2. In this project the idea of combining the two systems has been put into practice for the first time which makes this research innovative. It is necessary, if homeowners and developers are to be encouraged to obtain such systems, to test and prove their quality of the system so that people feel they are investing in something that has been tested and is reliable. Therefore this study was prompted in order to monitor the performance of the combined PPS/GSHP which was applied in 'real life' conditions with the expectation of achieving multi environmental benefits. When carrying out a project for the first time it is often expected to face some sorts of complications and the uncertainty of how well a system will perform in real life since no experience has been gained from previous applications. In the current study, the PPS/GSHP constructed at the Innovation Park at BRE, Watford and connected to a domestic setting (the EcoHouse) has proved its workability in terms of allowing rainwater to infiltrate leaving the surface free from rainwater ponds or runoff, using the constructer as rainwater storage, conjoining the GHE and so forth. However, having the PPS/GSHP constructed in real life (i.e. on site rather than in a lab experiment) has given the chance to observe problems that might occur when installing the system in reality. One of these problems occurred during the construction of the PPS/GSHP reservoir when a large concrete slab was found while excavating on the site which prevented the depth of the reservoir from surpassing 350mm. The other complication was the HGV that stood on the pavement causing the joints of the impermeable layer to weaken resulting in a gap(s) in the side(s) of the reservoir. Using such a shallow reservoir with the leakage problem through the gap(s), to provide heat to the domestic setting used in the current study (the EcoHouse) was a challenge. These issues together with the aims and objectives are addressed in this chapter.

9.1 The validity of installing the integrated PPS/GSHP system

A discussion of the PPS/GSHP installation in terms of: a) the depth; b) location; c) size of heat pump and paved area is presented in the following sections.

9.1.1 Installing the PPS/GSHP in a 350mm deep reservoir

The decision of installing the combined system in such a shallow depth was based on ensuring that the GHE is continuously immersed in water since it has been verified (from previous case studies mentioned in section l.3) that GSHPs perform better in saturated environments due to water acting as a heat transfer medium. Nonetheless, as a result of installing the system in a reservoir 350mm deep, ground temperatures surrounding the tank of PPS/GSHP combined system were greatly influenced by the ambient air conditions. In summer time (from April to September), the average temperature of the ground at 200mm and 350mm from the pavement surface where rainwater was stored was only a few tenths of a degree above 14°C and ambient temperature was around 15°C, whereas in winter (from October to March) the ground average temperature at the same depths was about 3 -

4°C and ambient temperature just above 5°C. Consequently, thermal energy extraction was accomplished through a non-equilibrated ground temperature. This resulted in the relatively unstable performance of the combined system with CoP ranging between 0.9 – 4.9.

Furthermore, it was observed that during the colder periods in the winter, the rainwater stored in the PPS/GSHP reservoir (350mm deep) dropped below freezing point, while rainwater stored in the PPS (500mm deep) never froze. This can be related, apart from the fact that the PPS/GSHP is 150mm shallower (i.e. the stored rainwater was closer to the pavement surface therefore more influenced by the severe conditions of the ambient air), to the smaller amount of rainwater actually stored due to leaks at the side(s) of the reservoir. If there had been no gaps in the sealed impermeable layer, a bigger volume of rainwater would have been stored and it might not have frozen, depending of course on the patterns of rainfall, the amount of runoff stored inside the reservoir, and the temperature of the rainwater (Gan *et al.*, 2007). It has been concluded by Gehlin & Nordell (1997), Pahud & Matthey (2001), Yari & Javani (2007), and Kharseh *et al*. (2011) that the temperature of the ground from which the GHE extracts heat is one of the main factors influencing the thermal performance of GSHP systems. Therefore, the shallow depth of the stored rainwater due to the gap(s) will have affected the CoP since the GHE was at some events extracting heat from a surrounding with a temperature below freezing point (this is discussed further later in this chapter).

As mentioned above, the system in this study was affected strongly by climatic conditions because the GHE was buried close to the ground surface. In other studies, horizontal GHEs were placed deeper than that applied in this study, for example 0.5m (Singh *et al*., 2010) and 1.8m (Gan *et al*., 2007), and these have given a different range of CoP values. It must be noted that comparability between these studies is difficult because of the variations between climatic conditions and the type of the surrounding medium, along with heat pump specifications and the mode in which the systems were operating (whether providing heating or/and cooling). Nonetheless, the influence of the ambient air temperature at different depths has been reported by different researchers. For example, Wu *et al*. (2010) clarified in their study that environmental conditions influenced 'soil' temperature up to a depth of around 0.5 m; whilst Tarnawski and Yuet (1988) concluded that at a depth of 0.8m the CoP is less affected by ambient air temperature fluctuations. A study by Ooka *et al*. (2007) revealed that ground temperature was significantly influenced by ambient air temperature up to 1m below the ground surface. Omer (2008), on the other hand, concluded that ground temperature stays constant at depths below 1.2m, whilst Rawlings & Sykulski (1999) suggested that at depths of less than 2m the ground temperature will show marked seasonal variation above and below the annual average air temperature. Almost all studies, however, confirmed that as the depth of the horizontal GHE increases, the response to weather changes reduces and the maximum and minimum ground temperatures begin to lag behind the temperatures at the surface, and consequently the performance of the system is higher (ASHRAE, 1995b).

The outcomes from this study show that a reservoir with a depth of 350mm is too shallow and that the profile of ground temperature is almost the same as the ambient air temperature profile. Therefore, it is more beneficial to install a deeper reservoir to put the pipe deeper into the ground so that the effect of the ambient air during winter can be mitigated, and in addition to which the risk of frost can be avoided. It is worth bearing in mind, however, that selecting a reasonable earth coil depth for the combined system as a compromise between performance and installation cost is essential, since deeper burial adds significant excavation costs to the overall cost of the system (ASHRAE, 1995b; Florides and Kalogirou, 2007), leading to an unacceptably long payback period.

9.1.2 The location of the installed PPS/GSHP

In a study by Gonzalez *et al*. (2012), changes in soil shading and soil moisture content due to the growth of vegetation were investigated and it was found that this was the main cause for soil temperatures to change, i.e. becoming cooler, whereby a drop in soil temperature was observed 0.25 m below the surface. Based on this, it can be said that having the PPS/GSHP located between two buildings at the BRE site (the Visitor Centre and the EcoTech building – see Figures 6-2 and 6-4) was preventing the pavement from receiving enough solar energy which could help in recharging the subsurface by providing additional heat to the heat transfer fluid during the year, consequently increasing the available energy for extraction. The importance of charging the ground with heat encouraged some researchers to combine the GSHP with a solar collector; an example of this arrangement is presented in Wang *et al*., 2010.

Another feature of the PPS/GSHP reservoir used in this research is that it was located 30m away from the building envelope, therefore heat loss from the pipes connected between the reservoir and the heat pump carrying the circulated fluid was more likely to happen. This adds a negative effect with regard to the efficiency of the heat pump. Installing the system a) closer to the heat pump, and b) with the coil at a deeper depth, should mitigate the influence of ambient air on the performance of the system. If it is not possible to avoid installing the PPS/GSHP distant from the heat pump, maybe it is worth considering Ozyurt & Ekinci's (2011) approach to overcoming the heat loss problem, namely by insulating the 2m deep pipes connecting the GHE to the evaporator thus minimising heat loss.

It should also be noted that at the location of the study i.e. the EcoHouse on the Innovation Park at BRE, lots of visitors, for example pupils on school trips, were permitted to walk around the building. It was noticed that certain actions (such as doors and windows being left wide open thus allowing cold air (in winter) to enter the building) led to the likelihood that false temperature readings were taken during some periods. It was also noticed on some occasions that the settings of the control panels inside the house had been changed, another factor that could influence the veracity of the CoP calculations based on temperature readings taken inside the house.

9.1.3 Possibility of inadequate design

An adequate design is necessary for PPS/GSHPs to meet performance expectations and have fewer maintenance issues. However, it is especially important in cold climates for the design of PPS/GSHP systems to match the parameters of the location. Poorly designed systems, with issues such as improper GHE pipe length, flow rate of heat transfer fluid, spacing of GHE, depth of GHE and so on (Healy & Ugursal, 1997) can result in a number of problems. For example, installing insufficient GHE pipe length could lead to excessive heat extraction and temperature drop in the ground near the slinky. Such heat extraction may not be thermally recovered throughout the year (Cottrell, 2009). Excessive on-off cycling can stress the heat pump unit and reduce its operational efficiency. In some cases inadequate GSHP performance can be due to oversizing the heat pump; aiming to provide more heat is a problem, primarily, of colder climates. The installation of an oversized heat pump will require a higher capital cost than necessary in the first place, followed by more electricity consumption and lower overall efficiency achieved. On the other hand, the use of a smaller, more efficient, and appropriately sized heat pump would have a significant impact on improving the system performance.

In the current study, it was observed from the 10-minute interval data that indoor temperatures of the monitored dwelling during heating mode were on some occasions around 30°C, which is considerably higher than the accepted comfortable temperature for inhabited spaces. This is probably due to installing an unsuitably sized heat pump. The use of a smaller, more efficient, and appropriately sized heat pump would have a significant impact on improving the system performance. Additionally, it could be tempting to increase the excavated area in order to increase the amount of GHE contact with the ground, consequently increasing the heat transfer. Nonetheless, an adequate design and an appropriate size of the area used for the reservoir, should help in meeting the system performance expectations. This should also make the system even more attractive to homeowners since avoiding an over-sized design would reduce up-front expenses, hence adding advantages to the number of benefits that can be received by applying a PPS/GSHP.

The uncomfortable observed temperature may also be due to an over-capacity in the paving system for heating, which was a result of installing the GHE under 65 m^2 of paving. If it is possible to install the combined system under a reduced paving area, it could attract more householders to apply the geothermal paving system as they could see it as a viable renewable energy choice that brings multiple benefits by using the combined system, including the potential financial savings for the home-owner in cold seasons.

The following section discusses the CoP of the combined system used in this study.

9.2 The performance of coefficient of the GSHP used in the integrated system

The average value of the CoP calculated over the monitoring period of this study was 1.8, which is considered low compared to the average CoP of GSHP falling in the range of 2.5 – 4.0 (Omer, 2008). On the other hand, when the ground temperature measurements undertaken while the stored rainwater was frozen were excluded, it can be seen that the combined PPS/GSHP system has a higher CoP (of 2.3) than those presented in Hepbasli *et al*. (2003) and Kara (2007). In the former study (Hepbasli *et al*., 2003), the GHE was buried at 50m, and the CoP value of the whole system calculated to be 1.34. In the latter (Kara, 2007) the GHE was buried at 55m while the CoP of the system came out at 2.09. Despite the exchanger pipe in those studies being much deeper (and, thus, much less affected by environmental conditions) than the GHE in this study, the CoP obtained from the PPS/GSHP reservoir is higher than that reported in both Hepbasli *et al*. (2003) and Kara (2007). This can be attributed to the GHE coil being submerged in rainwater, which enhanced heat transfer (Fan *et al*., 2007).

Nonetheless, comparison of the CoP values from this study with the values from other studies centred on GSHP systems was found to be unhelpful due to reasons explained earlier (the depth of the GHE, the properties of the climate, ground and so on of the places where the evaluations were conducted were different, as well as the experimental settings (such as backfill/surrounding material (soil, clay, water), length of pipe, distance between pipes.) were all different. In studies that used a similar set-up to this study, using a combined PPS/GSHP system, for example Grabowiecki (2010), who set up the combined system in wheelie bins located indoors and outdoors in Edinburgh, the CoP values in heating mode for the outdoor rigs were found to be 1.5 - 4.4. Similar results were found by Tota-Maharaj, 2010 in a similar set-up. There is, however, insufficient clarity on the expected CoP of cold climate GSHPs due to a lack of independently monitored GSHPs over periods greater than one to two years.

The other factor from the present study that can have a negative effect on the PPS/GSHP performance was the low levels of stored rainwater; consequently the GHE was not completely immersed in the harvested rainwater due to the gap(s) mentioned earlier in the membrane on the side(s) of the reservoir. Thus part of the pipe was exposed to ambient air conditions through voids between the sub-base material which has a lower thermal conductivity than water; therefore, as a transfer medium it is less effective (Omer, 2008).

The 1.8 CoP for the days on which heating was provided means that the installed system cannot be considered as a viable renewable source of energy under the 2009 EU Renewable Energy Directive, since a CoP of 2.875 or above is required (Sârbu and Sebarchievici, 2010). Even when the days on which ground temperatures of less than 1°C were excluded, the CoP (2.3) was still considered 'low' in terms of actually making a contribution towards renewable energy targets.

The prices of fuels such as mains gas or heating oil within the UK are much cheaper compared to the cost of electricity, as can be seen in Table 9-1 (Energy Saving Trust, 2012). The GSHP operates only on electricity, however, since this system has on average a CoP of 3-4 (see section 5.2), users should benefit from its relatively cheaper operating cost. Table 9-1 shows a comparison between the operating costs using different heating fuel. The table also gives a percentage efficiency assumption based on Energy Saving Trust (2012) for existing heating systems. The given efficiency is a reflection of the reduced amount of waste heat; the more efficient the heating system is, the more money on electricity can be saved (Energy Saving Trust, 2012).

Table 9-1: A comparison between the operating costs using different heating fuel (Table after Energy Saving Trust, 2012 - figures are based on current fuel prices of year 2012)

Fuel/operator	Average price (p/kwh)	Efficiency	Price of heat produced for customer (p/kwh)
Gas / boiler	4.49	78%	5.76
Oil / boiler	5.87	82%	7.16
Electricity / GSHP	14.39	350%	4.11

As shown in Table 9-1 the operating cost of GSHP is, although not by a huge difference, the least in comparison with the fuel-burning alternatives. Fuel prices continue their upward trend (DECC, 2011c), however, the increase of environmental problems awareness will probably inspire governments to increase their support and encouragement for the use of alternatives to fossil fuel through premium payment and incentives, which may lead to a cheaper operating cost when renewable energy is utilised instead of fossil fuel. The CoP for the system applied in this research at the EcoHouse, on the other hand, was 2.3 (i.e. efficiency 230%); hence, the price of heating produced for customers is 6.26 p/kwh (= 14.39/2.3). Therefore, a gas boiler would be rather more economical than a GSHP with such a low CoP.

The other drawback in respect of the PPS/GSHP low CoP is the emitted CO_2 which is almost the same (a little lower, to be precise) as a gas boiler as explained in the following calculations:

Emission factor for 'Electricity from grid' is 0.537 kg CO_2/kWh

For the PPS/GSHP system the CoP was 2.3

$$\therefore \text{CoP emitted is } 0.233 \text{ kg } \mathrm{CO_2/kWh}$$

Emission factor for 'Natural gas' is 0.185 kg CO_2/kWh

Efficiency of a gas boiler 78%

$$\therefore \text{CoP emitted is } 0.237 \text{ kg } \mathrm{CO_2/kWh}$$

Nonetheless, there were occasions on which the CoP did achieve the EU directive requirements; hence, it could be said that combining a GSHP with a PPS is feasible, however, burying the GHE in a deeper PPS/GSHP reservoir would be a solution for a better performance of the PPS/GSHP.

9.3 The potential influence of continuous heat extraction from the ground under realistic conditions on the ground thermal condition and on the performance of the system

The heating mode was the only setting applied in this study for the reasons explained previously in section 6.3.1. Since the UK is considered as having a relatively cold or at least 'cool' climate, it is probable that a PPS/GSHP will be used only for heating, unlike in more moderate climates where the ground may be used for both heat extraction (space heating) and rejection (space cooling). If the heat absorbed from the ground annually is not equal to the heat rejected to it, reduction in the ground heat may result (Boian and Iordan, 2008; Shuhong *et al*., 2009; Xi *et al*., 2011; Ooka *et al*., 2011; Yu *et al*., 2011). Accordingly, the earth energy of the PPS/GSHP was likely to not be balanced as there was no heat rejected to the ground, since the cooling mode was not put into operation.

As a conclusion, the system's efficiency during the heating mode was affected negatively since heat was extracted from ground that was influenced by: a) the cold ambient air and b) the extraction of heat *without* any compensatory or balancing heat injection. Gonzalez *et al*. (2012) examined the effect of heat uptake from the ground by a horizontal ground heat exchanger installed at 1m depth on the soil's physical characteristics, particularly temperature (at between 0 and 1m depth) for a site in the south of the UK. It was found that extracting heat via the slinky pipe has influenced the surrounding soil by significantly decreasing its temperature reaching values of down to $|\Delta T| 3°C$ at 1.0m depth (where the coil was placed) and a further decrease (up to 5°C) when heating demand was increased (while the swimming pool was switched on). In the current study, GHE was placed at the bottom of the reservoir (between 200 and 350mm deep from the surface of the pavement), hence, ground temperature at 60mm and 130mm deep were higher by 3.6°C and by 2.3°C, respectively, since the top part of the reservoir was less effected by the heat extraction.

Furthermore, given Britain's climate and environmental conditions it is very likely that if ground temperatures near the GHE generally fall due to heat extraction over the long term, the ground may not be able to completely recharge for the following season during the summer; hence this could lead to a reduction in GSHP performance over time.

The other aspect regarding freezing was an observation that during very cold conditions the top surface of the rainwater stored in the reservoir froze, while at the bottom the harvested rainwater remained in its liquid form. This finding was in contrast to studies concluding that ground freezing starts around the coil, for example, in an early study by Mei and Emerson (1985) and in a recent study by Eslami-nejad and Bernier (2012). These different observations are probably related to the medium surrounding the coil. The coil in the current study was surrounded by rainwater instead of soil; therefore, during the freezing process of the PPS/GSHP, similar to the freezing of lakes and ponds, ice forms at the top of the body of water, in contrast with set-ups in which the coil is buried in soil where freezing of the ground begins to happen in the immediate vicinity of the geothermal heat exchanger, as the studies mentioned above have shown.

A review of the literature has revealed that in the majority of studies it was found that long-term extraction of heat energy from the ground causes a degradation in ground temperature over time (Li *et al*., 2005; Singh *et al*., 2010; Wang *et al*., 2010; Ozyurt and Ekinci, 2011; Xi *et al*., 2011; Gonzalez *et al*., 2012). The results from the current study show that the system was performing intermittently, therefore it was not feasible to obtain data for a long period of operation. However, the ground temperatures where the GHE was placed in this study were found to be considerably lower than those at the top of the reservoir during the period of continuous extraction determined in this study (section 8.2). This is most likely due to heat extraction, it is however not certain due to the strong influence of the ambient air.

To have a clear picture of the effect of extracting heat from the ground on the ground temperature profile at the four different depths, a similar set-up of the PPS/GSHP reservoir (but without a GHE) should be installed at the same site for the purpose of comparison. This concept was applied in a recent study by Wu *et al*. (2010), from which it was concluded that the effect of heat extraction could be observed up to a distance of around 900mm from the heat exchanger, 250mm below the ground surface. In light of this, and as the total depth of the reservoir installed at this study was only 350mm, in addition to the influence of ambient air temperature, the extraction of heat must have contributed to the dropping of ground temperature - predominantly at the bottom of the reservoir but also in the top layers. A long-term study with continuous measurements of ground thermal condition will help to clarify and understand the thermal degradation of the ground over periods when heat extraction is occurring. The imbalance of heat extraction (space heating) versus heat injection (space cooling) from/to the ground, and the possibility of the ground freezing during the heating season are documented in the literature. However, few evidence of permanent ground temperature degradation has been reported, and few long-term studies have been carried out to determine the effect of GHE on ground thermal condition.

Results from this study indicated that when the temperature of the stored rainwater was lower than 1°C, the CoP remained constant at around 1. The behaviour of the PPS/GSHP system when the GHE is surrounded with frozen rainwater is not yet clear. Studies on systems with similar settings, such as those by Grabowiecki (2010) and Tota-Maharaj (2010) have not reported on the effects of the stored rainwater freezing. A number of other studies with the GHE buried in soil have been published, but the impact of freezing ground on system performance has not been addressed. For example, Nordell and Alström (2007) reported that, in rare cases, freezing occurring in the borehole water-fill creates a high pressure that flattens the pipe system, thereby upsetting the circulation of the working fluid. Fan *et al*. (2007, 2008), investigated the impact of coupled heat conduction and groundwater advection on the heat transfer between a vertical borehole and its surrounding soil. The system was operating under the following three conditions: (a) storing cold energy into soil (charging) during off-peak periods at night in summer; (b) providing air-conditioning by releasing the cold energy stored in soil (discharging) at daytime, where thawing and freezing took place periodically in the soil surrounding the GHE during summer air-conditioning periods; (c) supplying heat to buildings in winter. Relatively few studies, for example Fukusako *et al*. (1987), Fan *et al*. (2007) and Yang *et al*. (2010) have attempted to model heat transfer in the ground under freezing and thawing conditions for geothermal applications. Fukusako *et al.* (1987) investigated the heat transfer characteristics of a combined system made of a concentric-tube thermosyphon and a heat pump, and were able to account for ground freezing in the vicinity of the tube. Yang *et al*. (2010) investigated various alternate operational characteristics of a combined solar-GSHP system. A 2-D mathematical model with freezing/melting phase changes was developed. It was recommended to inject solar energy when the heat pump was not operating in order to achieve faster ground temperature recovery. The effect of ground freezing on system design and performance was, however, not evaluated.

9.4 Collecting temperature readings for a GSHP setting at a 10-minute interval

Regarding the sensors used in this study for the purpose of studying the performance of the heating/cooling system, two of the set-up considerations might be discussed a) the frequency of data collection, b) locations at which the sensors are placed. In terms of the intervals of data collection, different settings were reported in the literature, for example, Esen & İnallı (2009) used a 30-minute interval to measure the temperature distribution development in a borehole system with a GSHP over time. Hong *et al*. (2009) also recorded the indoor temperatures of the dwelling at the centre of their study twice a day (at 8am and 7pm). In a study presented by Dinse *et al*. (2004), whereby a heat pump water heater was installed with a storage tank to preheat water for a gas-fired hot water system with multiple recirculation loops, a data logger collected temperature data from different monitoring points including the inlet and outlet ground loop water, at 15-minute intervals. In contrast, a much longer interval is found in the work carried out by Fordsmand and

Eggers-Lura (1981), who suggested using a daily reading for calculating the CoP. On the other hand, Yu *et al*. (2010) collected indoor temperature data for an archive building; Jalaluddin *et al.* (2011) collected temperatures of inlet and outlet circulating water, and the temperature distributions of the ground and GHE tube wall at varying depths; both authors collected data every minute. Taking into consideration that a 1-minute interval would generate very significant computation time and data storage, the data logger in this study was set to collect readings every 10 minutes. This adjustment of data interval collection is similar to the settings in Michopoulos *et al*. 2007 and Chiang *et al*. (2012).

In terms of locating the sensors for monitoring purposes, several approaches have been described in the literature. In the study by Llovera *et al*. (2011) on the design and performance of a solar energy-efficient residential house located in the Pyrenees, in Andorra, one sensor was located in an exterior wall in the north façade together with a solar radiation sensor on the south façade of the three-storey single family house were installed in order to measure the exterior temperatures. Makaka *et al*. (2008) installed one sensor on the interior side of a north-facing wall and another one on the south-facing wall to measure the indoor wall surface temperatures, while a sensor on the surfaces of the exterior walls at each side of the building were used to measure the external temperatures. Boait *et al*. (2011) measured the room temperature by locating a sensor towards the centre of a building that was monitored in a study investigating the performance and control of domestic GSHPs in retrofit installations. In this current study, installing four sensors indoors and another four outdoors, on each side of the building, was done in order to get a complete picture of the temperature distribution at the EcoHouse, and also to avoid recording readings from only one side of the building that may have been subject to certain effects (i.e. thermal zoning, such as the sun's radiation falling on a certain side of the building for a longer time than on the other sides) that would distort the data collected for the indoor and outdoor conditions and result in an inaccurate picture of the building's thermal profile.

Chapter 10 : Conclusion

This project focused on studying the feasibility and performance of a SuDS technique combined with a renewable energy system for heating purpose at a domestic setting. This required continuous monitoring and close observation of the EcoHouse connected to the PPS/GSHP. The monitoring process that was applied in this study involved installing sensors in different locations at the site, gathering temperature data every 10 minutes. This generated a significant amount of data which were used to get a wider picture of the performance of the combined system operating under real conditions. The key findings are presented, followed by recommendations for further study.

10.1 The key findings

The 'tanked' PPS/GSHP is a viable technique that brings multiple benefits, therefore it is recommended that it be used whenever is appropriate. It has proved to be a reliable system that can control rainwater runoff by allowing infiltration through the gaps between the pavement blocks. On the other hand, it could be argued that the 'tanked' PPS/GSHP is not acting as a sustainable drainage system since runoff, to a certain extent, is prevented from percolating naturally through the soil due to the impermeable layer which forms the water tight reservoir so that the GSHP uses the water as a heat transfer medium. Despite this *downside* of the combined PPS/GSHP, the benefits that the system provides, such as using the stored water for secondary usage, treating the runoff before it is released, providing cooling/heating at virtually any location and reducing electricity bills, may compensate for stopping runoff infiltrating into the ground.

Furthermore, it was found that the rainwater harvesting apparatus and GSHP provided the 3-bedroom detached house with enough heat, and that comfortable internal temperatures were recorded inside when the external temperature was very low. Nonetheless, the daily temperature inside the EcoHouse showed little stability over the years of monitoring and was uncomfortably cold due to plumbing problems, system repair events, electricity shutdowns and so on.

A PPS/GSHP system with the GHE installed in a 350mm deep reservoir is highly susceptible to the influence of the ambient air, even at the bottom of the reservoir. The ground temperatures measured during monitoring led to the conclusion that there was not much difference between the temperatures of the ground at different depths of the reservoir. A statistical correlation analysis ($p<0.01$) was computed for the relationship between the climatic conditions and ground temperature, and a correlation of 0.787 was found. The system is likely to be inefficient in terms of electricity demand if the PPS/GSHP is installed at a depth that is influenced by climate conditions. Under severe cold conditions, the rainwater stored in the shallow reservoir froze. It took the stored rainwater a longer time to thaw in comparison with ice or snow on the surface of the pavement since the process of conduction heat transfer is relatively insignificant. Thus, the GHE was on such occasions in a frozen surrounding which had a negative affected on the CoP.

The setup of the PPS/GSHP used in this project showed significant correlations ($p<0.01$) between the CoP, the outdoor air temperature and the ground temperature, with total correlation values of 0.700 and 0.926, respectively. It was found that when the stored rainwater temperature was below 1°C, the CoP was 1 or less; heating provided during such events was completely derived from the electricity mains.

The PPS/GSHP had a low CoP of 1.8, hence the system cannot be considered a satisfactory renewable source of energy under the 2009 EU Renewable Energy Directive since a CoP of 2.875 is required. Measuring water depth inside the PPS/GSHP reservoir throughout the monitoring period indicated that, due to leakage, the level of the stored water was low, which resulted in parts of the coil not being covered with water. The low CoP of the system, apart from the strong influence of the ambient air, may be linked to the bare coils since an inappropriate heat flux and heat exchange would have occurred due to there not being enough volume of rainwater. The leakage problem emphasized the necessity of following the PPS/GSHP reservoir installation requirements and indications.

Continuous heat extraction from the ground contributed to an underground temperature drop. However, the influence of the ambient air added a complication to whether it was possible or not to be certain that the drop in ground temperature was only due to heat extraction.

The PPS/GSHP had no impact on cooling the thermal profile of the air near the surface of the pavement. This is most likely related to the Inbitex composite layer preventing evaporation from occurring. In the UK, there is surplus of rainwater, therefore evaporation should not be a problem, and maybe cooling the atmosphere above the surface of the pavement is not essential.

10.2 General Findings

- Measurement of rainwater level in the PPS/GSHP reservoir showed a gradual decrease in the volume stored, which suggests that the gap(s) at the sides of the reservoir became larger over the monitoring period.

- The ground temperature of the reservoir in comparison with the ambient air temperature was cooler on hot days, and was warmer during cold days. Furthermore, seasonal analysis revealed that ground temperature was cooler than air temperature in summer, but also cooler in winter.

- Measuring the temperature on the surface of the external walls yielded high temperatures, up to 50°C. This suggests the potential for installing solar panels on the external surfaces of the wall and connecting the panels to the reservoir in order to enhance the ground temperature for a better performance of the PPS/GSHP.

10.3 Critiques, lessons learned and repeatability

- The building was constructed by Hanson Formpave, the monitoring kits were installed by OpenHub, the heat pump was installed by the Geothermal International company, whose contract ended while the study was running, and the EcoHouse was managed by BRE, meant that plurality in responsible agencies had the effect of slowing down problem solving after they were reported.

- It is necessary to follow in their entirety the instructions for installing a PPS/GSHP provided by the supplier and/or the installer and avoid ignoring restrictions, such as that regarding the limits for traffic load on the pavement, since this is likely to be the reason why a gap or gaps in the welded joints of the reservoir occurred.

- The PPS/GSHP was located between two buildings and was 30m away from the domestic setting. Such a set-up would have a negative influence on the performance of the system as the buildings would prevent sunlight from reaching and charging the surface of the pavement, and the distance between the reservoir and the building would result in heat loss. All of which will weaken the performance of the PPS/GSHP.

- The location and the number of sensors, and the 10-minute interval generated a massive amount of data, which meant manipulating and analyzing it was a challenge, however a significant amount of information was provided. Nonetheless, it is important to have access to the collected data. This will help in an immediate identification of problems such as a sudden drop in the internal temperatures which indicates, for example, a plumbing problem that caused the system to stop working; or noticing a gap in the collected data which then can be soon fixed, consequently avoiding the problem of missing data.

- It is highly recommended to study the performance of the system in a building without public interference. Monitoring a building with controlled access should help in understanding causes of having unreasonable or unusual data readings.

- It should be considered to use the cooling along with the heating mode in further research since this should help in balancing the ground temperature.

- In further research it should be ensured that the combined system is installed deeper than 350mm. This study recommends installation arrangements for the PPS/GSHP to be in a reservoir that is greater than 350mm deep.

10.4 Recommendations for a further study

Further analysis and data collection (for example, weather conditions including rain intensity, snow, ice, sunlight hours and intensity, humidity, wind speed), electricity consumption, and water temperature before and after entering the heat pump are required to continue to develop the understanding of the performance of the PPS/GSHP when used for heating domestic dwellings, and ensuring to take into consideration points mentioned in the ‘lessons learned’ section will help to achieve an optimal use of the combined system. Additionally, having a family or a certain number of people occupying the EcoHouse as part of a further study is suggested in order to report the performance of the system on a daily basis. This would allow for consideration of the variables, which may influence indoor temperatures, and reporting on any changes in the system’s settings.

It is worth applying both heating and cooling, so that the ground thermal properties are partially restored. It is also desirable to install a PPS/GSHP and a PPS at the same site under the same climatic conditions, but also with the same specifications (depth, area, location and surrounding) for comparison purposes.

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Appendix

Appendix 1: Calculations of the potential number of observations

Observation duration:

- EcoHouse :	**2008 -**	12 March - 31 December
	2009 -	01 January - 31 December
	2010 -	01 January - 21 November
-PPS/GSHP reservoir:	**2008 -**	08 August - 31 December
	2009 -	01 January - 31 December
	2010 -	01 January - 30 March
- Bollard:	**2008 -**	08 August - 31 December
	2009 -	01 January - 31 December
	2010 -	01 January - 30 March

Taking in consideration the number of days each month:

- **31 days** → January, March, May, July, August, October, and December
- **30 days** → April, June, September, and November
- **28 days** → February

Hence number of days of monitoring

- EcoHouse :	2008 -	295 days	
	2009 -	365 days	
	2010 -	325 days	**∑985**

-PPS/GSHP reservoir:	2008 -	146 days	
	2009 -	365 days	
	2010 -	89 days	**∑600**

- Bollard:	2008 -	146 days	
	2009 -	365 days	
	2010 -	89 days	**∑600**

Consequently, the potential number of observations are:

- **House temperature**

$$= 985\ days^{1} \times \frac{24\ hr}{1\ day} \times \frac{60\ mins}{1\ hr} \times \frac{1\ observation}{10\ mins} \times 9\ locations$$

$$= 1{,}276{,}560\ observations$$

- **PPS/GSHP reservoir temperature**

$$= 600\ \text{days} \times \frac{24\ hr}{1\ day} \times \frac{60\ mins}{1\ hr} \times \frac{1\ observation}{10\ mins} \times 4\ locations$$

$$= 345{,}600\ observations$$

- **The bollard temperature**

$$= 600\ days \times \frac{24\ hr}{1\ day} \times \frac{60\ mins}{1\ hr} \times \frac{1\ observation}{10\ mins} \times 2\ locations$$

$$\approx 172{,}800\ observations$$

∴ Potential total observations = 1,794,960

[1] Number of days of monitoring